Coastal Geomorphology of Great Britain

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Chapter 7

Sandy beaches and dunes – GCR site reports

INTRODUCTION

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Sandy beaches and their backing dunes are a common feature of the British coast. Although the European Commission's CORINE project recorded 9.6% of the British coast to be sandy beach (European Commission, 1998), this statistic did not include any cliff-foot beaches. Sand beaches and dunes occur throughout the British coast, but are concentrated mainly on the northern and western coasts. For example, 75% of coastal dunes, by area, occur north of the Tees and Solway Firth and sand beaches occur in association with dunes and other sandy structures. Sand beaches also commonly form the lower parts of beaches where shingle ridges occur close to high-water mark. They also occur below many cliffs, for example, the chalk around the Isle of Thanet, Kent, the cliffs of eastern England from Flamborough Head to Essex, and along much of the Cornish and Welsh coasts, as well as in association with sand cliffs and other strata that yield sand as a major fraction of weathered debris (Figure 7.1).

Since sand supplies from the upper beach are usually required to build sand dunes, the fact that sandy beaches and dunes commonly co-exist is unsurprising. However, some sandy beaches are not backed by dunes, mainly owing to limited throughput of sand, an unfavourable wind regime or lack of availability of a site suitable for deposition.

The relationship between sandy cliffs and beaches has typically been described in the context of beach sediment budgets, beach management and coast protection (e.g. Clayton, 1989b; Psuty and Moreira, 1990; Bird, 1996). Extensive sand cliffs (for example at Bournemouth, Dorset, and Culbin, Moray, and, more widely, along the coast of the Algarve in Portugal and much of the coast of California) often have substantial sand beaches at their foot. Much of the supply of sand from sand cliffs in southern and eastern Britain has been reduced in recent years by coastal protection schemes. For example, before they were progressively protected by sea walls during the 20th century, the Bournemouth cliffs (some 11km in length) produced about 115 000 m^3 of sediment annually (of which 80% was coarse enough to stay on the beaches). By the mid 1980s, this supply had fallen to 4000 $m^3 a^{-1}$, coming mostly from the unprotected cliffs to the east (Halcrow Maritime, 1999).

A number of writers have argued for a 'systems approach' to sandy beach study, a point also made strongly in respect of cliffed coasts by Brunsden (1973). Such an approach allows each of the influencing factors affecting beach and dune form to be examined in isolation in order to determine its effect. This methodology allows the links between process and form to be better identified. Therefore, much of the investigation of sandy beaches has focused on changes in beach profiles in response to variations in weather conditions, especially wind, and on beach sediment budgets. Long-term trends in beach morphology and the relationship between beach and dune morphology and ecology typify many other studies. However, it is also apparent from the evidence of GCR sites described in this chapter that change in many sand and dune systems is associated with high magnitude/low frequency events superimposed on the more routine processes. Similarly the relationship between many subsystems that make up these features function over different timescales and with different intensities. For example, the sandy beach and dunes at Gibraltar Point, Lincolnshire, comprise many different subsystems, which include nearshore tidal ridges, a ridge-and-runnel foreshore, and a backshore with arcuate foreshore dune ridges and dune slacks. The spit protects the upper beach ridge sheltering an area of mature (Old Marsh) from New Marsh by a storm beach, which resulted from an occasional extreme event in the evolution of the area. More change occurred in a few hours in 1922 than during years of normal sedimentation; isolation of the storm effects helps in gaining an understanding of the relative importance of both frequent and infrequent events and evolution. This is a theme that is common to many other sand coast GCR sites: Spurn Head on the Holderness coast responded dramatically to a surge in 1849 and both Spurn Head and Gibraltar Point showed different reactions to the 1953 surge. In terms of the development of sub-parallel dune ridges, Gibraltar Point offers considerable contrasts to the GCR site at South Haven Peninsula, Dorset, mostly because of different tidal and wave conditions and differences in sediment supply. In particular, Gibraltar Point lies in a macrotidal and South Haven in a microtidal environment. In both of these sites the processes operating in one subsystem have important repercussions in

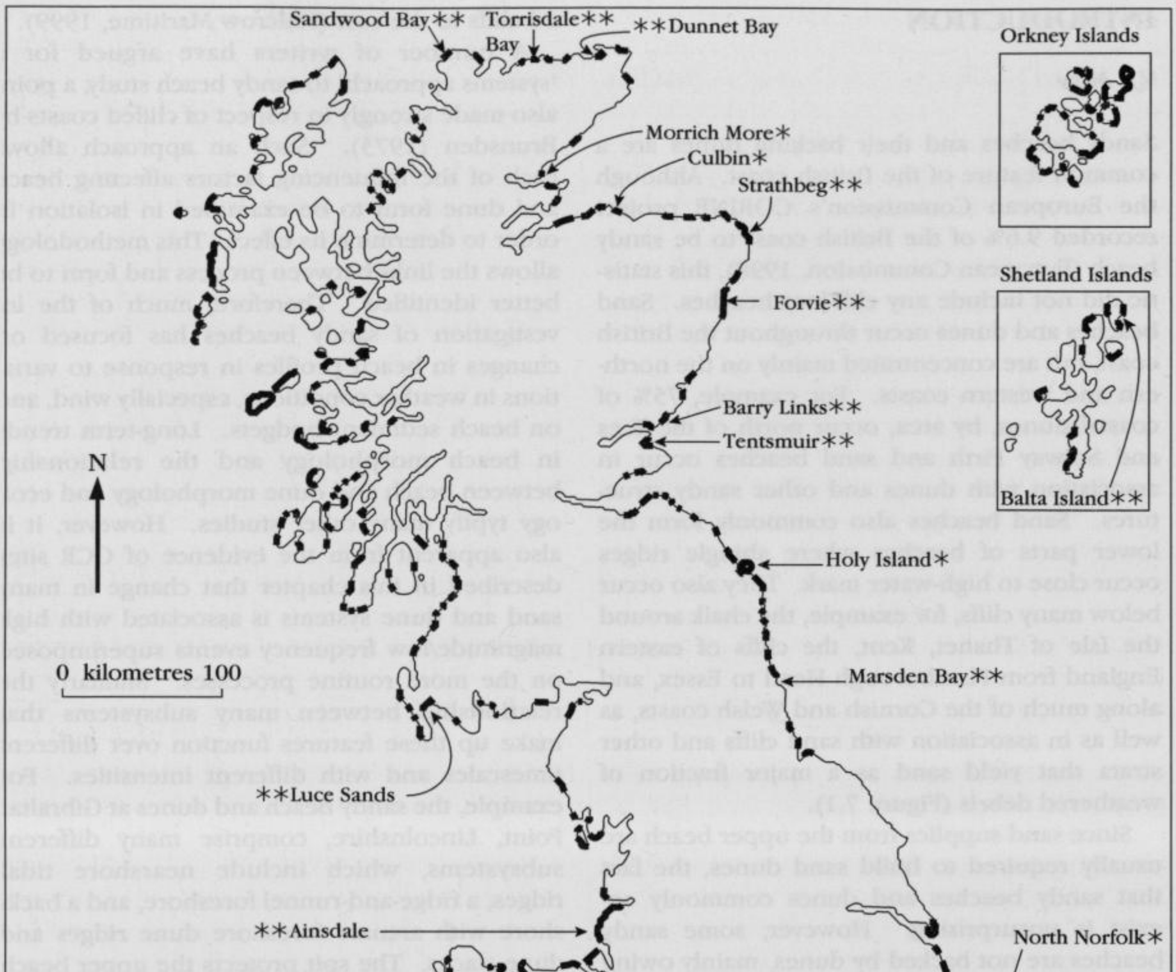

Figure 7.1 Great Britain sandy beaches and coastal dunes, also indicating the location of GCR machair-dune sites (see chapter 9) and other coastal geomorphology GCR sites that contain dunes in the assemblage.

all of the others.

It is evident from the GCR sites described in this chapter (Figure 7.1 and Tables 7.1 and 7.2) that both beach and dune features co-exist and depend upon the availability of sand that may come from the seabed, from fluvial sources and from cliff erosion, depending upon their geomorphological setting. Small sand beaches can develop with very limited sediment supplies. For example, small sand beaches form localized pockets within embayments of the Thanet chalk coast and the indented rocky coasts of south-western Britain and northern and western Scotland. Sand commonly forms a veneer on some shore platforms and displays a range of minor current- and wave-related forms.

In the Chalk, sand derives from attrition of flint and from the release of fossil shell fragments from the chalk itself. Elsewhere, sandstone and soft sediment cliffs provide large quantities of sand to their beaches, which may then be transported alongshore. Erosion of the till coast and shallow seabed off Holderness provides very large volumes of sand and gravel annually that are transported both alongshore to form a large sand spit at Spurn Head and into the North Sea. Along the coast of East Anglia, very large volumes of sand and gravel are derived from erosion of till cliffs, but there are also large volumes in offshore banks that result

Table 7.1 Main features and present-day sediment sources of dune types. Exemplar sites described in the present chapter are in **bold** typeface. See also Table 7.2. (Based on Ranwell, 1972.)

Type	Sediment sources	Geomorphological setting	Wind directions	Exemplar GCR sites
Foreshore dunes				
Spit dunes	Intertidal banks and longshore	On promontories at estuary mouths with near-parallel or radiating ridges and slacks	More common with onshore prevailing and dominant, but not restricted to this	**Forvie, Strathbeg, South Haven Peninsula**, Morfa Harlech, Holy Island (Goswick and the Snook), Culbin, Morrich More
Prograding ness dunes	Accretion at ness, possibly with longshore sediment supply from opposite directions alongshore	On open coast	Prevailing and dominant winds from opposite directions (offshore/ onshore)	Winterton Ness, **Barry Links, Tentsmuir**
Offshore island dunes	Offshore, longshore and intertidal drying banks	Offshore or barrier islands narrow, subject to washover, often display time-series development in main direction of longshore transport	Can occur with both onshore and offshore prevailing winds	Scolt Head Island, Blakeney Point recurves (North Norfolk Coast), Pembrey (Carmarthen Bay), Culbin, Morrich More
Hindshore dunes				
Bay dunes	Restricted in longshore direction	Usually at bay head on indented coasts	Prevailing onshore	**Dunnet Bay, Luce Sands, Upton and - Gwithian Towans, Tywyn Aberffraw, Oxwich Bay Sandwood, Balta Island, Torrisdale Bay and Invernaver**
Hindshore dune system	Offshore and intertidal	Extensive sandy coasts	Prevailing and dominant winds from the same direction	**Braunton Burrows, Newborough Warren, Ainsdale**, Holy Island (Ross Links)
Hindshore sand plains	Offshore, intertidal and beach	Bay-head and low-lying rocky coasts	High wind-speeds that restrict vertical development	**Tywyn Aberffraw**

from the offshore transport of longshore sediment. The sand beaches here largely result from the continued throughput of sand. On the more indented coast of the western and northern British Isles, sand beaches are commonly found in embayments where sand cannot escape, and in estuaries and firths, where sand from landward and seaward sources is locally plentiful. Many beaches that are dominated by gravel at the shoreline are also characterized by extensive, sandy, lower beaches. Similarly many beaches formed in heterogeneous materials are sorted locally into sand and gravel for short periods of time and the sand may be blown into sand dunes to the rear of the beach.

Although this chapter covers sandy beaches as well as dunes, there is little further introduction to beaches that has not been covered in Chapter 5. However, is Marsden Bay, County Durham, is exceptional, where a sandy (and locally mixed sandy gravel) beach lies at the foot of Magnesian limestone cliffs. This was the site of pioneering work on beach mobility in response to variations in wind and waves over 50 years ago (King, 1953), and for that reason is the first site covered in this chapter. For the rest, wide, sandy beaches are usually associated with – and indeed allow the formation of – dunes, but given their varied location, their varying exposure to waves and their range of tidal conditions, they show considerable differences from place to place.

Sand dunes are most likely to be associated with stable and accreting beaches, with a wide upper beach that allows drying and sediment movement by strong winds. A typical example is the west-facing beach of Dunnet Bay in Caithness, a sand trap with onshore winds. Other wide beaches, especially where they are not fully open to the ocean (as around the Irish Sea) and so have waves with more limited fetch, are frequently barred, with ridges and runnels, as at Ainsdale, Lancashire (see GCR site report). Other barred beaches are found at Holkham Bay, North Norfolk, which is a prograding beach, and Braunton Burrows, Devon, as the aerial photograph (Figure 7.9) demonstrates.

Most beaches are more likely to be suffering erosion than progradation (Bird, 1985), and this is certainly true of the UK. The exceptions are in northernmost England (e.g. Holy Island) or parts of Scotland, where postglacial isostatic rebound has offset present-day sea-level rise. As a result, these wide, prograding beaches are backed by some of the largest dune fields in Britain, particularly where sediment was moved onshore during the later part of the Holocene sea-level rise, such as in much of Scotland. It is no surprise that 71% of the dune area of Britain is in Scotland. With the virtual stabilization of sea level, many beaches have lost volume and dune cliffing has become more common throughout Britain. In places, climatic and/or sea-level changes have led to an oscillation between dune cliffing and dune growth on varying timescales, such periodic cliffing maintaining some dynamic stability via contributions of sand to the fronting beach. In general, present sea-level rise and lack of new sediment means that cliffed dunes are more common than active foredune growth in Britain.

The sandy beaches described in this chapter are only a small sample of the important beach sites included in the coastal geomorphology 'Block' of the GCR, since the great majority of the GCR sites have sandy beaches of one type or another. Chapters 9 and 11 also include descriptions of sandy beach and dune sites where such features are an important part of the coastal geomorphological assemblage. The great depositional sites of Morrich More in the Dornoch Firth and Culbin in the Moray Firth, the Northumbrian coast around Holy Island, the North Norfolk coast and Rhossili Bay (Carmarthen Bay GCR site) all provide unmodified, dynamic examples of some of the finest sandy beaches to be found in the UK.

Coastal dunes

There are over 295 separate coastal dune sites around Great Britain (shown on the small-scale map in Figure 7.1), the largest of which attain over 8000 ha in area. Their total area is about 70 000 ha of which 71% by area are in Scotland (Dargie, 2000).

Most British dune systems originated when substantial seabed deposits were moved onshore during the early and middle part of the Holocene Epoch and began to be deposited close to their present locations from about 6500 years BP. In some areas where the sea-level history is more complex, such as in the Western Isles of Scotland, the arrival of dune sands first began about 8700 years BP and may have been non-synchronous between sites (see Chapter 9; Hansom and Angus, 2001). Dune systems such as those at Ainsdale and Braunton Burrows can be shown to have developed over the past six

Table 7.2 Main features, sediment sources, tidal ranges of sandy beach and dune GCR sites, including coastal geomorphology GCR sites described in other chapters of the present volume that contain dune features in the assemblage. It should be noted that all of the machair sites in Chapter 9 have dune features (see Table 9.1). Sites described in the present chapter are in **bold** typeface.

Site	Main features	Other features	Present-day sediment sources	Tidal range (m)
Marsden Bay	Beach phases	Cliffs and stacks	Local cliff erosion – small	4.2
South Haven Peninsula	Shore-parallel dune ridges, originating from the 16th century, slacks, sand-spit	Relict and active cliffs, caves, rock platform	Longshore – restricted Offshore – significant	1.5
Upton and Gwithian Towans	Climbing dunes, exhumed bedrock base	Stacks	Offshore – restricted	5.8
Braunton Burrows	Large dune field, parabolic dunes, slacks	Ridge and runnel	Intertidal and estuarine	7.3
Oxwich Bay	Bay-head beach and dunes	Cliffs and emerged platform	Offshore – limited	8.2
Tywyn Aberffraw	Sand plain, isolated parabolic dunes shore-parallel linear dunes		Offshore, probably in deficit	4.7
Ainsdale	Large dune field, slacks, ridge and runnel, long dated history		Offshore – limited – in deficit	8.3
Luce Sands	Bay-head dunes	Holocene emerged gravel ridges	Onshore and longshore – significant	5.6
Sandwood Bay	Dynamic beach–dune complex, climbing dunes	Gravel-cored bar, blowouts	Offshore and recycled – limited	4.2
Dunnet Bay	Bay-head dunes and sand plain	Blowouts	Offshore – limited	4.0
Balta Island	Climbing dunes	Beach–dune–grassland continuum	Local – limited	1.9
Strathbeg	Shore-parallel dune ridges, large blowouts	Holocene emerged gravel ridges	Longshore – restricted, loch outlet source	3.3
Forvie	Shore-parallel dune ridges, originally moved as waves northwards		Longshore – cycled from estuary	3.1
Barry Links	Foreland sand plain, linear parabolic dunes		Estuarine, longshore – limited	4.4
Tentsmuir	Shore-parallel dune ridges–intertidal sands		Estuarine and longshore – significant	4.4
Torrisdale and Invernaver	Beach–dune, hill-top dunes, glaciofluvial terraces	Archaeological context	Offshore and fluvial recycled – now limited	4.0
Morrich More	Shore-parallel beaches and dunes: sandplain	Holocene beaches and cliffs	Offshore – restricted	4.3
Culbin	Shore-parallel dunes, large dune field now stabilized by forest	Holocene emerged gravel ridges and spits	Longshore –restricted, offshore – limited	3.6
East Head	Small spit-based dunes		Intertidal	3.4
Holy Island	Dune field, spits, barrier beach	Cliffs, Holocene saltmarsh, intertidal mudflats	Longshore, offshore – significant	4.1
Dawlish Warren	Parallel spit-based linear dunes	Recurved spit	Intertidal and possibly estuarine In deficit	4.1
North Norfolk Coast	Major mainly linear dunes	Spits, barrier beach	Longshore and offshore	6.4–4.7
Morfa Harlech	Linear shore-parallel dunes		Longshore – restricted, estuarine	4.5
Morfa Dyffryn	Linear shore-parallel dunes, blowouts, dunes invading slacks		Longshore – restricted, offshore	4.3
Winterton Ness	Linear dunes on cuspate foreland		Longshore	2.6
Ynyslas	Spit-based dunes		Longshore – restricted, estuarine	4.3
Carmarthen Bay				
Pendine	Shore-parallel linear dunes		Offshore, estuarine to distal end	8.0
Pembrey	Large dune field, spit-based linear dunes		Offshore and estuarine	8.0
Whitford spit	Estuary-mouth spit		Longshore, drying intertidal	8.0
Laugharne Burrows	Cliff-top dunes		Local redistribution, drying intertidal	8.0
Newborough Warren and Morfa Dinlle	Major dune field, parabolic and linear dunes, spit, tied island and slacks	Saltmarsh	Offshore and estuarine	4.7

Table 7.3 Calcium carbonate content of upper beach/foredune in selected coastal geomorphology GCR sites. Sites described in the present chapter are in **bold** typeface. (Based in part on Goudie, 1990, and various sources cited by Ritchie and Mather, 1984.)

Dune location	$CaCO_3$ (%)	Median grain size (phi)
Culbin	0.0	2.0
South Haven Peninsula	0.015	?
Lossiemouth	0.26	2.0
Tentsmuir	0.4	2.5
Luce Sands	0.5	2.4
Forvie	0.55	1.9
Buddon Ness (**Barry Links**)	1.0	2.0
Walney Island	1.51	2.21
Morfa Dyffryn	3.34	2.31
Ainsdale	3.57	2.13
Invernaver	3.8	1.9
Morfa Harlech	3.96	2.13
Newborough Warren	4.56	2.50
Ynyslas	4.98	2.29
Strathbeg	7.86	2.0
Rattray (**Strathbeg site**)	9.10	1.9
Laugharne (Pendine)*	11.15	2.40
Morrich More	12.0	2.4
Pembrey*	12.04	2.33
Oxwich Bay	12.45	1.93
Tywyn Aberffraw	13.20	2.47
Llangennith*	15.65	1.63
Braunton Burrows	19.59	2.13
Dunnet Bay	20.4	1.7
Dunbar	20.4	1.5
Westward Ho!	21.79	2.45
Machir, Islay	33.6	2.2
Mangersta, Lewis	38	1.4
Luskentyre, Harris	44	2.0
Traigh na Berie, Lewis	47	2.4
St. Ninian's Tombolo, Shetland	47.5	2.0
Balnakiel	52.0	1.8
Hayle (**Upton and Gwithian Towans**)	56.80	1.56
Loch Gruinart, Islay	59.0	2.1
Eoligarry, Barra	80.0	2.0
Ardivachar, South Uist	84.0	1.7
Balta Island, Shetland	95.5	1.8

* Carmarthen Bay

millennia, especially from the evidence of preserved peat associated with dune slacks and larger wetlands that developed shorewards of the coastal beaches. In contrast, other dunes are more recent, for example at South Haven Peninsula the dunes have formed since the 16th century. Some dunes, for example at Culbin, Moray, Newborough Warren on the Isle of Angelsey, and Hayle and Upton and Gwithian Towans, Cornwall, have migrated inland covering buildings and farmland. British dunes tend to be located:

1. in areas of high tidal range,
2. where prevailing winds provide the main means of landward aeolian transport, and
3. in association with estuary mouths dominated by large sandy sediment loads or at the heads of inlets and bays,
4. on north-eastern coasts, where strong winds from the north and east provide the means for landward aeolian transport e.g. the coasts between Aberdeen and Fraserburgh and Northumberland.

Narrow, linear-dune systems occur along eastern coasts that are associated with sandy estuaries or high tidal ranges, but the size of the dunes is generally much less than those of the exposed and windy western coasts, even though the intertidal sandy area may be very extensive.

There are few significant dunes on the eastern coast of England, apart from the dunes around Holy Island, Northumberland, and along the Lincolnshire and north Norfolk coasts. Between the Tees and the Tamar there are 24 dune sites (*c.* 8%) and between the Tamar and the Mull of Galloway 67 dune sites (*c.* 23%). The remaining 204 (*c.* 69%) sites lie along the coast of Scotland and the English coast north of the Tees. The largest area of dunes is in north-west Scotland, particularly in the Outer Hebrides where machair predominates (Ritchie and Mather, 1984; Dargie, 2000; see Chapter 9). Of 43

Table 7.4 Variations in calcium carbonate content and pH in foredunes and main dunes. (Based on Salisbury, 1952; and Willis, 1985)

Location	Calcium carbonate content of dunes		pH	
	Foredunes	Main dunes	Foredunes	Main dunes
South Haven Peninsula	0.015	0.01	7.0	3.6
Southport (near Ainsdale)	6.0	0.2	8.2	5.5
Braunton Burrows	20.0	8.5	9.05	8.2
Blakeney Point, North Norfolk Coast	0.6	0.02	7.3	4.2

nationally important sand dune sites, only six lie on the south or east coast (Doody, 1985).

The foredunes around the coast of England and Wales are notable for their generally low calcium carbonate content (Table 7.3). Goudie (1990) shows that of 42 foredune areas in England and Wales, 29 had less than 20% $CaCO_3$. The highest values occur between Land's End, Cornwall, and Woolacombe, Devon, and along the south coast of Pembroke, with many greater than 50%. The highest $CaCO_3$ content in England and Wales occurs in Constantine Bay, Cornwall (87.5%). Studland Bay, Dorset, in contrast, has almost no $CaCO_3$ (only 0.015%). There is also a tendency for the main dunes to have lower $CaCO_3$ and pH than the foredunes (Table 7.4). The very high $CaCO_3$ content of the foredunes of the south-west coast is probably a result of the high concentrations of shell debris. The more carbonate-rich sands also tend to be coarser with mean D_{50} (median grain size value) of 1.75 phi (Goudie, 1990). This, with their comparatively low density and often platy form, may make them more readily transported by wind (Goudie, 1990). Where the main source is estuarine, the grain size is usually smaller. Scottish dunes and beaches, and especially machair, tend to follow a pattern of very high $CaCO_3$ content where biogeneic sources predominate often reaching extremely high values (Mather and Ritchie, 1984; e.g. Balta Island has 95.5% shell sand, see GCR site report in the present chapter).

On much of the southern coast of Britain, sand was in plentiful supply for dune building at the end of the main Holocene rise when sea level attained present levels about 6500 years BP. In recent centuries, however, the supply of sand has diminished significantly and erosional conditions generally prevail.

In England, few southern or eastern dunes are accreting, the most important exceptions being at Holy Island and South Haven Peninsula, and even the latter is affected by erosion of its older southern beach and dunes. In contrast, on western and northern coasts, dunes are common features, reflecting the combination of plentiful sand supplies mainly from the seabed in the past, but also from upland river catchments, and the effects of prevailing onshore winds. However, many are now affected by wave erosion of their fronts either by occasional storms or by long-term changes in sea-level and storminess, together with reduced sediment supply. Prior to 6500 years BP sand supply for dune building was plentiful, but it is now much reduced, and, as a result, frontal dune erosion is commonplace (Hansom, 1988; Hansom and Angus, 2001).

The conservation value of sandy beaches and dunes

Dunes are geomorphologically important because of:

1. their natural dynamism and the relationship with their ecology
2. their role in preserving and then exhuming Holocene sedimentary sequences and
3. their role in coast protection.

The selected GCR sites (Table 7.2) include the beach and dune sites that best exemplify the different ways in which the physical coast responds to the effects of climate, waves and currents when there is a substantial and continuing provision of sand-sized sediments. They are areas of both progradation and erosion which provide a highly dynamic foundation for some of Britain's most important sites for fauna and flora. Internationally, they have been recognized by geomorphologists as exemplifying especially well the ways in which coastal dunes form, change and are modified.

Most dune systems around the British coast are complex, and very few have individual isolated stable dunes within them. English east coast dunes are generally narrow, have only limited periods of onshore winds, and lack large and constant sand supplies. Many of those on the west coast lie upon bedrock surfaces of varying height and so lack the level foundations of sand plains. They also have usually had ample supplies of sand in the past that have produced a complex dune topography in which dunes are at many stages of development and sand is transferred from erosional phases to depositional ones (for example at Newborough Warren and Morfa Dyffryn). Tywyn Aberffraw is an important member of the network of dune systems because of its relatively limited sediment supply and restricted development of dunes. In this respect it contrasts especially strongly with its neighbour at Newborough Warren.

In this chapter the site reports are ordered in a clockwise fashion starting with the Marsden Bay GCR site.

Dunes and sandy beaches as biological SSSIs and Special Areas of Conservation (SACs)

In Chapter 1, it was emphasized that the SSSI site series is constructed both from areas nationally important for wildlife, and GCR sites. An SSSI may be established solely for its geology/geomorphology, or its wildlife/habitat, or it may comprise a 'mosaic' of biological and GCR sites that may be adjacent, partly overlap, or be co-incident. There are a number of sand dune and beach sites that are crucially important to the natural heritage of Britain that are notified as SSSIs primarily for their wildlife value, but implicitly will contain interesting coastal

Table 7.5 Candidate and possible Special Areas of Conservation in Great Britain supporting Habitats Directive Annex I coastal dune habitat(s) (other than machair) as qualifying European features. Non-significant occurrences of these habitats on SACs selected for other features are not included. (Source: JNCC International Designations Database, July 2002.)

SAC name	Local authority	Dune habitat extent (ha)
Barry Links	Angus	447.6
Braunton Burrows	Devon	767.5
Carmarthen Bay Dunes/Twyni Bae Caerfyrddin	Abertawe/ Swansea; Caerfyrddin/ Carmarthenshire	780.2
Coll Machair	Argyll and Bute	409.0
Culbin Bar	Highland; Moray	612.9
Dawlish Warren	Devon	28.2
Dee Estuary/ Aber Dyfrdwy*	Cheshire; Fflint/ Flintshire; Wirral	4.0
Dornoch Firth and Morrich More	Highland	974.4
Dorset Heaths (Purbeck and Wareham) and Studland Dunes	Dorset	95.9
Drigg Coast	Cumbria	519.8
Durness	Highland	386.7
Humber Estuary*	City of Kingston upon Hull; East Riding of Yorkshire; Lincolnshire; North East Lincolnshire; North Lincolnshire	529.0
Invernaver	Highland	54.2
Kenfig/ Cynffig	Pen-y-bont ar Ogwr/ Bridgend	673.8
Limestone Coast of South West Wales/ Arfordir Calchfaen de Orllewin Cymru	Abertawe/ Swansea; Penfro/ Pembrokeshire	397.1
Monach Islands	Western Isles / Na h-Eileanan an Iar	215.1
Morecambe Bay	Cumbria; Lancashire	220.5
Morfa Harlech a Morfa Dyffryn	Gwynedd	228.6
North Norfolk Coast	Norfolk	387.3
North Northumberland Dunes	Northumberland	1078.6
North Uist Machair	Western Isles / Na h-Eileanan an Iar	963.3
Oldshoremore and Sandwood	Highland	165.3
Penhale Dunes	Cornwall	422.4
Saltfleetby–Theddlethorpe Dunes and Gibraltar Point	Lincolnshire	265.6
Sands of Forvie	Aberdeenshire	469.7
Sandwich Bay	Kent	258.3
Sefton Coast	Sefton	1072.7
Solent Maritime	City of Portsmouth; City of Southampton; Hampshire; Isle of Wight; West Sussex	113.2
Solway Firth	Cumbria; Dumfries and Galloway	32.6
South Uist Machair	Western Isles / Na h-Eileanan an Iar	545.7
Tiree Machair	Argyll and Bute	237.4
Torrs Warren–Luce Sands	Dumfries and Galloway	819.5
Winterton–Horsey Dunes	Norfolk	44.7
Y Twyni o Abermenai i Aberffraw/ Abermenai to Aberffraw Dunes	Gwynedd; Ynys Môn/ Isle of Anglesey	672.3

* Possible SAC not yet submitted to EC.

Bold type indicates a coastal GCR interest within the site.

geomorphology features that are not included independently in the GCR because of the 'minimum number' criterion of the GCR rationale (see Chapter 1). These sites are not described in the present geomorphologically focused volume.

The importance of dunes as areas of national ecological significance was recognized and described by Tansley (1939, 1945) and Steers (1946a, 1953a). Soon after the Nature Conservancy was established in 1949, it designated a number of major dunes as National Nature Reserves, including Braunton Burrows, Newborough Warren, Ainsdale and Holy Island. The *Nature Conservation Review* (Ratcliffe, 1977) confirmed the great importance of dunes as part of the network of nationally significant sites.

In addition to being protected through the SSSI system for their national importance, certain types of dune are Habitats Directive Annex I habitats, eligible for selection as Special Areas of Conservation (see Chapter 1). The Directive identifies a suite of dune vegetation types (see below), representing the succession from dune initiation to mature, stable dune habitat. Collectively, these types encompass almost the full range of coastal dune habitats present in the UK.

Dune SAC site selection rationale

The sites are, for the most part, the most extensive examples in the UK and have the best conserved structure and function, demonstrating transitions between Annex I types, while also representing the range of geographic and ecological variation of each habitat type.

- **Embryonic shifting dune** vegetation exists in a highly dynamic state and is dependent on the continued operation of physical processes at the dune/beach interface. It is the first type of vegetation to colonize areas of incipient dune formation at the top of a beach.
- **Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')** encompass most of the vegetation of unstable dunes where there is active sand movement. Under these conditions sand-binding marram *A. arenaria* is always a prominent feature of the vegetation and is usually dominant.
- **Fixed dune vegetation** occurs mainly on the largest dune systems, being those that have the width to allow it to develop. It typically occurs inland of the zone dominated by marram *Ammophila arenaria* on coastal dunes, and represents the vegetation that replaces marram as the dune stabilizes and the organic content of the sand increases.
- **Decalcified fixed dunes with crowberry *Empetrum nigrum*** represent the later, more mature, stages of the successional sequence characteristic of sand dunes. Exposure to rainfall over long periods means that there is leaching of the surface layers, causing a loss of calcium carbonate and increased soil acidity.
- **Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)** occur on mature, stable dunes where the initial calcium carbonate content of the dune sand is low. The surface soil layers rapidly lose their remaining calcium carbonate through leaching, and become acidified.
- **Dunes with *Hippophae rhamnoides*** comprise scrub vegetation on more-or-less stable sand dunes in which sea-buckthorn is abundant.
- **Dunes with *Salix repens* ssp. *argentea*,** where creeping willow is dominant, forming prominent, low scrubby growth.
- **Humid dune slacks** are low-lying areas within dune systems that are seasonally flooded and where nutrient levels are low. Dune slacks are often rich in plant species.
- **Coastal dunes with juniper *Juniperus* spp.** comprises common juniper scrub in a variety of dune situations.
- **Machair** – see Chapter 9 of the present volume.

Table 7.5 lists coastal sand dune SACs, and indicates which of these sites are also (at least in part) important as part of the GCR and are described in the present chapter.

MARSDEN BAY, COUNTY DURHAM (NZ 400 650)

V.J. May

Introduction

Marsden Bay (see Figure 7.1 for general location) includes beach, rock and cliff features and is a classic locality for beach process studies, based on the work of C.A.M. King over 50 years ago (King, 1953). Until very recently, it was the only site where the behaviour of beaches resting against relatively resistant cliffs had been studied intensively. King's analysis of the relationship between beach profiles and wave conditions influenced much subsequent work on beaches, and as a result, the location is frequently cited in the literature. It is also notable for a suite of cliffs and shore platforms cut into the Permian Magnesian Limestone, which crops out only on this part of the British coast between the River Tyne and the River Tees, and it contains the best examples of stack and cliff development in this rock type. The Permian concretionary limestone is most common in the headlands, stacks and arches, whereas the bays are cut into a weaker dolomite. An intricate assemblage of forms has developed as local small-scale joints have been exploited by marine erosion. Although Marsden Beach itself is dominated by sand with some shingle, there are also cobble and boulder accumulations associated with both the cliff-foot and former stacks. This site remains better documented than any of the other small cliff-foot beaches that occur along the north-east coast of England.

Description

Marsden Bay is a small bay some 1200 m in length in the limestone cliffs between the rivers Tyne and Wear (see Figure 7.1 for general location). The site extends southwards beyond the bay itself to include parts of the cliffs towards Lizard Point (Figure 7.2). At the northern and southern extremities of the site the cliffs are about 15 m in height, but rise behind the bay to between 25 and 30 m. High spring tides reach the foot of the cliff throughout the site. There are no other sand or shingle beaches close to the site, and King (1953) suggests that it is unlikely that longshore transport carries any sediment into the bay. As a result, the only sources are the cliffs or the offshore zone; the cliffs themselves appear incapable of supplying the sand volume although they do supply limestone clasts. The beach faces north-east with a maximum fetch to the north of at least 1900 km. King chose the beach to compare the effect of the prevailing offshore south-westerly wind with that of the dominant onshore northerly wind.

The northern part of the site is dominated by cliffs much broken by caves, arches and a large stack. A platform cut in the limestone extends offshore for about 200 m and strongly refracts all waves approaching the cliffs. The foot of the cliff

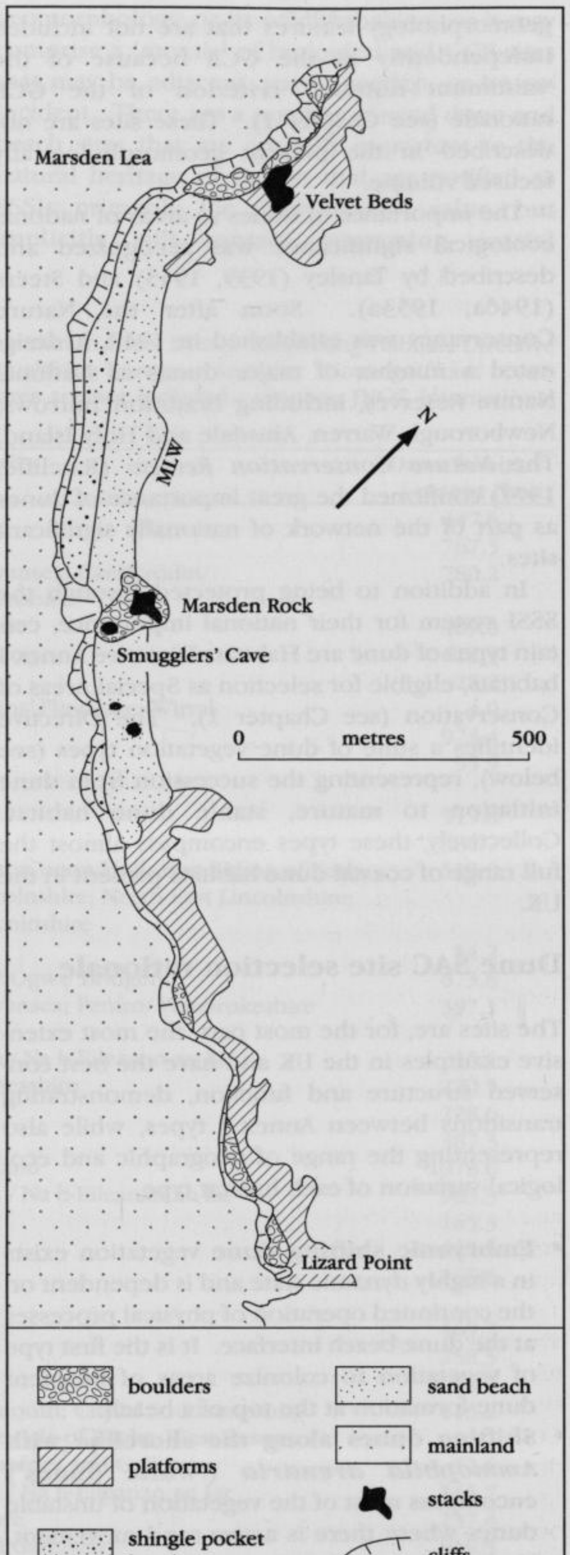

Figure 7.2 Key geomorphological features of Marsden Bay, Marsden Lea to Lizard Point.

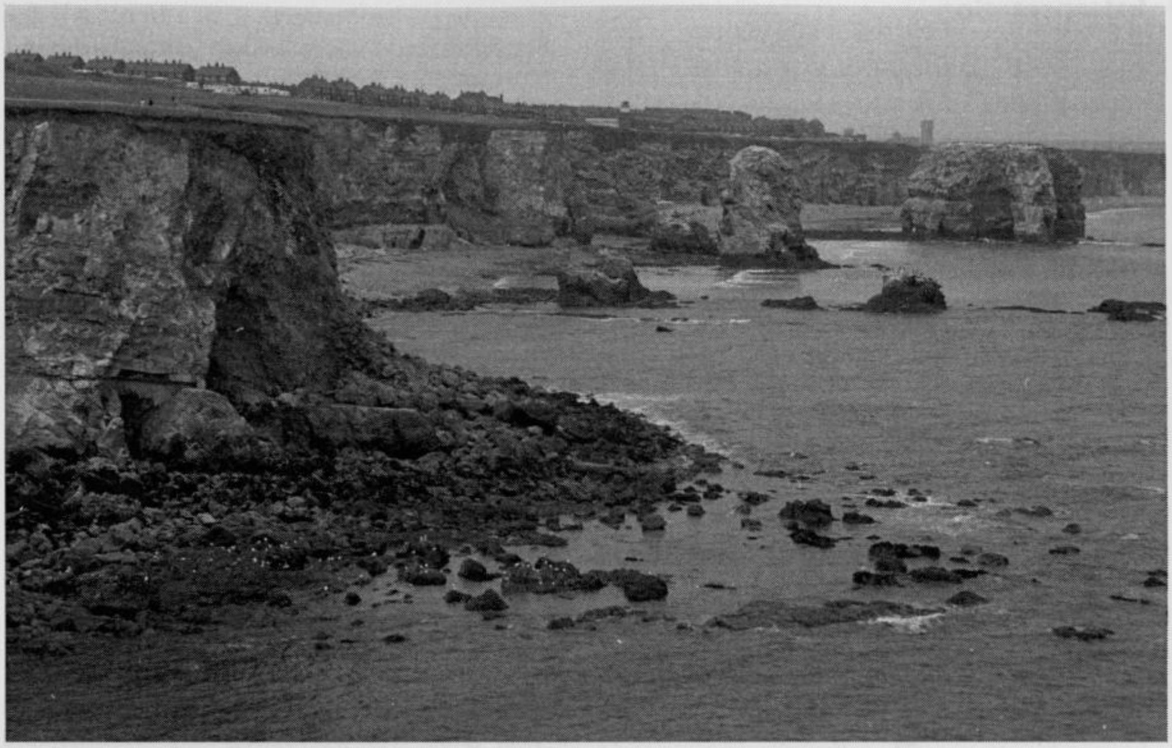

Figure 7.3 Marsden Bay – view looking towards the north-west showing the Magnesian Limestone cliffs and stacks and stumps. (Photo: V.J. May.)

is littered by cobbles and boulders of limestone, their size and shape being strongly controlled by the blocky nature of the local rock. Marine quarrying and abrasion exploit the numerous small joints in the limestone. There are several stacks and stumps towards the centre of Marsden Bay (Figure 7.3), which show evidence of being more strongly controlled by larger discontinuities. The two largest stacks have upper surfaces at 27 m and 24 m, i.e. about the same as the adjacent cliff top. In February 1996, the roof of the largest arch collapsed and Marsden Arch became a stack. The cliffs in the southern part of the site are more strongly controlled by the jointing pattern with short straight sections separated by sharp almost right-angle joint-controlled bends. Cobbles and boulders have accumulated within the resulting small bays.

King's 1953 paper describes the changes that occurred in the sandy beach profiles under certain well-defined conditions as follows.

1. Swell with an onshore wind produced long high waves. These were steep high-energy waves that proved very destructive, carrying sand seawards. Because these waves have a long period and are steep, the resultant beach was low and relatively wide.
2. Swell with an offshore wind produced long low waves. These flat waves are constructive, though with only moderate energy. Sand is moved landwards from the lower to the upper beach. The beach gradient remained low.
3. Local stormy sea with an onshore wind produced short high waves. These waves are very erosive, cutting into the upper beach and moving sand to the lower beach. Beach gradient is flat.
4. Locally generated waves with offshore winds produced short low waves. These waves are very flat and have little energy. Although they are constructive, the action is limited to a narrow zone, in which the beach gradient is steep as a result of the combination of both short period and flat waves.

King concluded that on Marsden Beach the prevailing offshore wind is associated with constructive wave action, and the dominant onshore wind with beach erosion.

Interpretation

King's 1953 paper was a significant step in the understanding of beach processes. Previously, most studies had concentrated upon spits and barrier beaches, such as those at Hurst Castle, Hampshire, and Scolt Head, Norfolk, and the behaviour of beaches that were free to transgress the land behind them. At Marsden Bay, the beach (composed of fairly coarse sand and gravel) rests against a cliff and so its long-term movements are controlled by the rate of retreat of the cliffs and the associated supply of sediment from them. Within those constraints short-term changes in beach profile are related to wave type and wind direction. Marsden Bay offers an opportunity for assessment of the effects that future sea-level change may have on cliff-foot beaches. As sea level rises, the tidal duration curve on a cliff-foot beach should move up the beach slope. Since the beaches at Marsden Bay appear to have retained a similar volume since King's surveys, they provide an opportunity for use as a baseline for process-response studies as the rate of sea-level rise changes.

The second reason for the importance of this site is the development of the stacks and caves in limestone dominated by small, closely spaced joints. Although the southern part of the site is controlled by larger, more widely spaced, joints, there are few stacks there. Other sites with comparable forms (e.g. the GCR sites South Pembroke Cliffs, Flamborough Head, Kingsdown to Dover, Ballard Down) have major joints that control either or both cliff form and cave–arch–stack development. In relatively weaker materials such as the Chalk and the Keuper Sandstone (e.g. the GCR site Ladram Bay) the presence of a more resistant layer at the foot of the cliff appears to be especially important in increasing the likelihood that stacks will develop (Precheur, 1960). Since these conditions appear to be unimportant in Marsden Bay, other factors such as the local structure of the Magnesian Limestone, its strength, the role of boulders in modifying the behaviour of waves locally, and the nature of the intertidal platform may all play a part. Much of the platform, for example, is covered by small boulders derived from the Magnesian Limestone. Their dimensions are strongly related to the blockiness of the limestone. Their presence makes the platform surface particularly rough when compared with many of the Chalk platforms farther south (for example Flamborough Head, Joss Bay, Kingsdown to Dover), and so wave quarrying at most states of the tide is likely to be less effective than where blocks are absent. However, abrasion might be enhanced where blocks occur. Variations in jointing along the cliffs may give rise to differences in rock strength that in turn affect the development of bays and headlands in the site, and these deserve further investigation.

Conclusions

There are two key features of this site:

1. It provides a benchmark for beach studies both because of its suitability for surveys continuing King's work in the 1950s and because that work provided a frequently cited demonstration that wind and wave conditions affect beach behaviour on much shorter timescales than the seasonal beach models elsewhere.
2. It represents cliff–beach–platform development in a rock type that is little represented along the British (or European) coastline, and offers an additional example of forms such as stacks and arches.

SOUTH HAVEN PENINSULA, DORSET (SZ 033 848)

V.J. May

Introduction

South Haven Peninsula on the southern side of the entrance to Poole Harbour (see Figure 7.1 for general location and Figure 10.2) is an excellent example of a prograding sandy beach that has been well documented in both the historical record and in more recent field surveys (Diver, 1933; Steers, 1946a; Arkell, 1947; Robinson, 1955; Carr, 1971b; May and Schwartz, 1981; Bray *et al.*, 1995; May, 1997b). Three main former ridges occur, each with dunes fronted by a seaward slope extending beneath alluvial deposits. Much of the seaward dune-system is prograding, and accretional forms characterize much of the strandline. However, the northern part of the site, known as 'Shell Bay', has been affected by erosion and the alignment of the beach as a result of the construction of a training bank alongside the main navigable channel to Poole Harbour. The southern part of the site extends to low cliffs at Studland that form the southern limit of the sediment cell that feeds the beach (May and Schwartz, 1981).

Description

This is one of the few prograding beaches in southern Britain; despite some erosion at its northern and southern extremities and intensive recreational usage, it retains many of the key features which were described by Diver (1933). South Haven Peninsula contains five sub-units.

1. A sandstone cliff (SZ 041 825–SZ 038 828) to the south of Redend Point cut in Bracklesham Group rocks of Eocene age that stands behind a wooded shingle and sand ridge and a modern beach of angular flint and some chalk and sandstone pebbles.
2. Redend Point (SZ 038 828–SZ 036 829). The most resistant part of the site, the headland comprises the Redend Member (formerly Redend Sandstone – Arkell, 1947) and has well-developed platforms, low cliffs and a series of small caves. The cliffs decline to the north and are affected by small landslides.
3. A narrow, fronting sand beach (SZ 036 829–SZ 034 837), which links the cliffs to the main beach at South Haven. Erosion along this section was sufficiently rapid during the 1980s and early 1990s to have stimulated some attempts to retard it using a vertical wooden revetment and gabions. Marram *Ammophila arenaria* was planted to help build up some dunes in front of holiday chalets. These occupy an area that once formed the southern end of the South Haven dunes; it is now severely degraded by trampling and so has been excluded from the site. During early 1996 the wooden structures were outflanked and destroyed and the front edge of the dunes cut back in excess of 4 m; a pattern repeated in early 1997.
4. The main area of the dunes (SZ 034 837–SZ 042 860) faces south-east and is prograding, apart from some erosion at the southern end in the vicinity of the main recreational facilities and the National Trust car park. This part of the site includes the former dune ridges described by Diver (1933), Little Sea, large wetland areas between the dunes, and the former sea cliffs which pre-date the formation of the dunes (Figure 7.4).
5. Shell Bay (SZ 042 860–SZ 036 867). This is the northern part of the sand dunes where they have been limited in their northwards growth by the deep-water entrance to Poole Harbour.

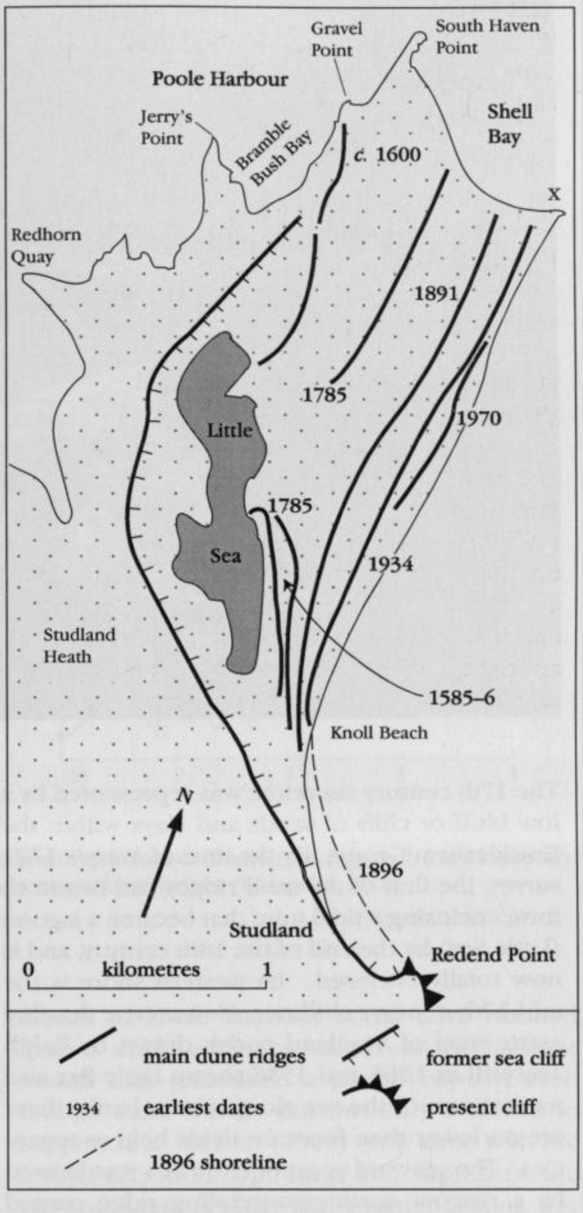

Figure 7.4 Historical dune development at South Haven. The 'Training Bank' extends south-eastwards from point X. (After Diver, 1933.)

Interpretation

Diver (1933) used the many maps of the entrance to Poole Harbour, from Saxton (1575) onwards, to interpret the history of the ridges of blown sand that form South Haven Peninsula.

Figure 7.5 View looking north-eastwards towards Sandbanks and Poole Harbour, with Shell Bay (SB) to the right foreground, to the east of South Haven Point (SHP). Gravel Point (GP) lies in the forground to the left (see Figure 7.4 for sketch map).

Brownsea Island, in the centre of Poole Harbour (see Figure 10.2, Chapter 10, for map), lies to the WNW of Sandbanks, just out of view. (Photo: © ukaerialphotography.co.uk.)

The 17th century shoreline was represented by a low bluff or cliffs of sands and clays within the Bracklesham Group. By the time of Avery's 1721 survey, the first of the sand ridges had begun to form enclosing a tidal inlet that became a lagoon (Little Sea) by the end of the 18th century, and is now totally enclosed. Its western shore is the mid-17th century cliffline. However, a detailed estate map of Studland parish drawn by Ralph Treswell in 1585 and 1586 shows Little Sea as a narrow arm of the sea along whose banks there are no fewer than fourteen fields held as tenancies. The seaward coast of Little Sea was formed by a narrow northward-trending ridge named 'Burnet poynte'. The western shoreline extended northwards to form a large recurve that, according to Treswell, had its distal end at 128 perches (641 m) from Brownsea Castle. Today, although the present tip of South Haven Peninsula lies twice as far (1200 m) from Brownsea Castle, a series of low intertidal gravel and sand ridges are exposed between South Haven Point and Brownsea Island. The northernmost tip of these ridges, known as 'Stone Island', lies about 500 m from Brownsea Castle. On the Poole Harbour side of the ridge there are four small headlands known in order from south to north as 'Rede orde', 'Coke orde', 'Geries orde' and 'Rickmans orde'; these co-incide in position with the modern Redhorn Quay, an unnamed ridge, Jerry's Point and Gravel Point. The southern three are formed in Bagshot Beds (Poole Formation) and gravels similar to others associated with former terraces of the Frome and its tributaries. There is no field sedimentary evidence to suggest that they represent former distal features of the South Haven spit, although it is possible that at one time the beach at Jerry's Point was linked to the spit. In contrast, the last, Rickmans orde (i.e. Gravel Point), lies in the approximate position where Diver located the distal end of the spit portrayed on Camden's 1607 map. In light of Treswell's survey it is now possible to regard the dunes at South Haven as having an earlier origin than Diver (1933) or later writers have suggested. The presence of salterns (sites of salt production) at the head of Little Sea (recorded as early as the Domesday survey (1086 AD; Thom and Thom, 1983) and tenanted enclosures on the ridge to seaward of the 16th century Little Sea suggest at least some stability to the feature.

The early dune ridges were fronted by a wide intertidal area of drying sand and the low tide limit was close to its present-day position. Indeed, even allowing for the limitations of comparison of maps and charts, the low-water mark has remained in more or less the same position

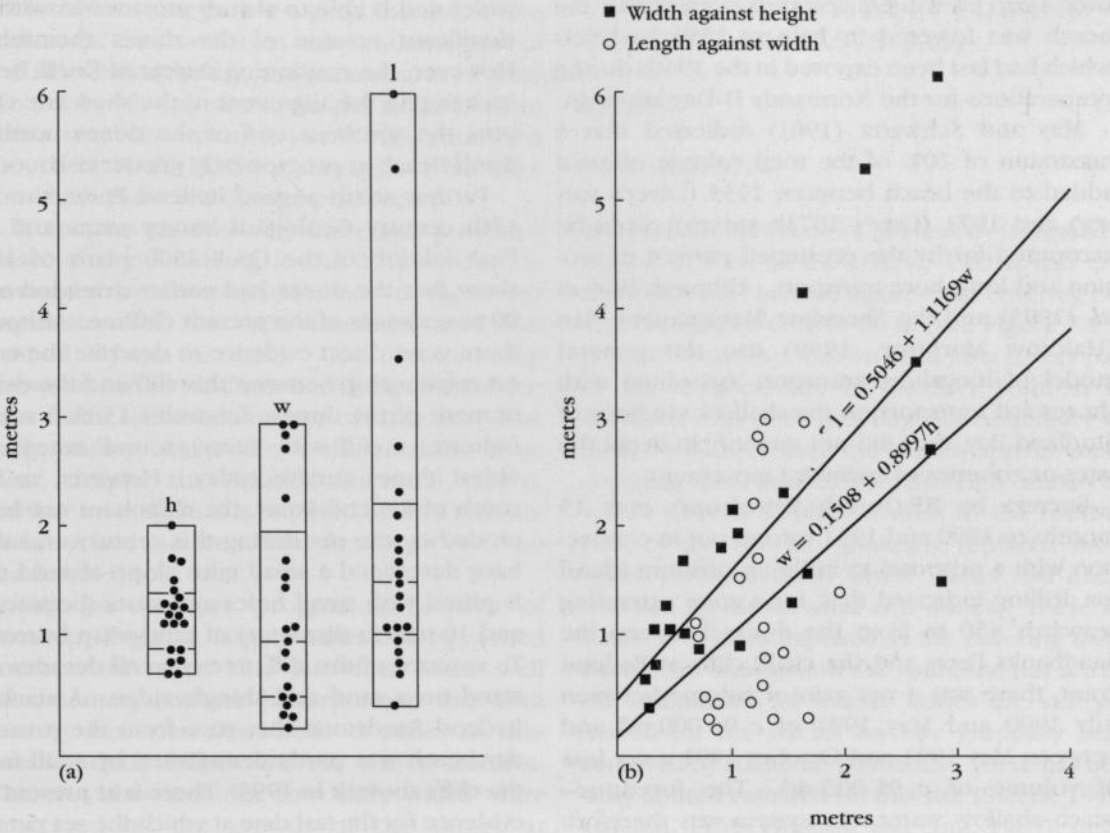

Figure 7.6 Cave relationships at Redend Point, South Haven Peninsula GCR site (see Figure 7.4 for location). (a) Cave height, h; width, w; length, l. (b) Relationships between cave height (h), and w and l.

for at least 200 years, a fact apparently overlooked by all previous writers. Robinson (1955) noted that the one fathom (*c.* 2 m depth) line had moved shorewards between 200 m and 300 m in the six decades following Mackenzie's survey of 1785. Ward (1922) considered that the northern spit at Sandbanks was supplied by sand moving from the east; Steers (1946a) supported the idea of a counter-drift of sand, i.e. from both south and north, towards the mouth of Poole Harbour. The entrance to Poole Harbour is deep, with a maximum ebb-tide current of 2.5 m s^{-1}. There is no evidence to suggest that its position has changed during the last few centuries. Robinson (1955) concluded that there was no evidence of such counter-drifting and proposed that the development of South Haven Peninsula resulted from a process of frontal accretion in which a series of beach ridges were built up parallel to the dominant waves, providing the foundation for the dunes. He went on to suggest that the apparent double spits at the mouth of Poole Harbour could have resulted from a single embankment across the harbour mouth that resembled a partial bay-bar, even though there was no documentary evidence to support this. Kidson (1963) took issue with the frontal accretion hypothesis and supported the view of Steers (1946a) that counter-drifting was a possible explanation for the double spits.

Using aerial photographs taken between 1936 and 1970, Carr (1971b) showed that erosion had occurred at the southern end of the dunes (a maximum of 0.8 m a^{-1}) and in Shell Bay (maximum 0.67 m a^{-1}), but accretion had been more typical of the main part of the dunes, gaining an average of 2.15 m a^{-1} and a maximum of 4.3 m a^{-1}. Since 1970, these trends have continued, although phases of accretion alternate with erosion, with some large erosion events affecting even the normally accreting shoreline. During periods of prolonged east winds (e.g. during early 1996), the dunes between Redend Point and the Knoll car park were cut back by over 4 m. Eyewitness accounts suggest that the beach was lowered in January 1996 to levels which had last been exposed in the 1940s during preparations for the Normandy D-Day landings.

May and Schwartz (1981) indicated that a maximum of 10% of the total volume of sand added to the beach between 1933 (Diver's survey) and 1971 (Carr's 1971b survey) could be accounted for by the presumed pattern of erosion and longshore transport. Although Bray *et al.* (1995) and the Shoreline Management Plan (Halcrow Maritime, 1999) use the general model of longshore transport associated with shoreward transport on the shallow sea floor of Studland Bay, they did not quantify in detail the rates or volumes of sediment movement.

Surveys by BP (British Petroleum) over 15 months in 1990 and 1991 carried out in connection with a proposal to build an offshore island for drilling indicated that, for a zone extending seawards 450 m from the dunes between the Sandbanks Ferry and the chalk cliffs at Redend Point, there was a net gain of volume between July 1990 and May 1991 of *c.* 90 000 m^3 and between May 1991 and October 1991 a net loss of volume of *c.* 91 000 m^3. The foredune–beach–shallow water area system was therefore in balance. The largest gains occurred within Shell Bay (more than 40 000 m^3 gained over a length of about 370 m) and the greatest losses in Shell Bay (over 32 000 m^3) and in the southern parts of the dunes (over 40 000 m^3). Over the 3 km from the Training Bank (the northern beach) to Knoll Beach, however, there was a gain in the first period of 23 890 m^3 and a loss in the second period of 19 436 m^3, a net gain of 4454 m^3. The net vertical gain over the whole of this area was 3 mm. There were considerable movements of sand within this zone, with erosion on individual profiles sometimes balanced by accretion within the same profile. The differences in quantities in individual profiles suggest that there are important local movements of sand within the shallow water zone that are not a simple longshore process of transport. These are not yet fully understood.

Since the 1990–1991 surveys, the general pattern of accumulation in Shell Bay and southwards from the Training Bank has continued. The northern beach has suffered several phases of erosion, as has the whole frontage southwards to Middle Beach. As a result, Middle and Knoll beaches are very narrow at high water. In contrast, the beach north of Knoll Beach is much wider and is able to absorb most waves without significant erosion of the dunes themselves. However, the continuing retreat at Knoll Beach is changing the alignment of the shoreline. This puts the southern end of the dunes north of Knoll Beach at progressively greater risk.

Farther south around Redend Point, the late 19th century Geological Survey maps and the First Edition of the OS 1:2500 plans of 1886 show that the dunes had earlier extended over 80 m seawards of the present cliffline. Although there is no direct evidence to describe the earliest relationship between this cliff and the development of the dunes, Treswell's 1585–6 survey indicates a cliff with 'furzy ground' where the oldest dunes survive today. However, to the south of Redend Point, the cliffs have not been eroded by the sea during this century and they have developed a small talus slope of sand that is pitted with small holes and casts (between 6 and 10 mm in diameter) of sand-wasp burrows. To seaward of the cliff, trees several decades old stand on a sand and shingle ridge. A stack of Redend Sandstone that rose from the present-day beach was partly demolished by a fall from the cliffs above it in 1995. There is at present no evidence for the last date at which the sea cut the cliffs.

The development of caves and a shore platform in the Redend Sandstone demonstrates a clear link with near-vertical joints in the sandstone. Most of the caves are narrow clefts in the rock, but some are semi-circular in cross section with considerable evidence of the effects of abrasion in the morphology of the cave floors. The floors are usually continuations of the platform across which it is possible to trace some of the joints. Figure 7.6 shows that the longer caves tend to be both higher and wider than shorter caves, probably caused by structural controls. Potholing occurs both on the platform and within the caves, sometimes in association with the truncated parts of pipes within the sandstone. This is a very rare feature, the only other site where planed-off pipes have been reported being to the west of Cuckmere Haven, Sussex (Castleden, 1982). Marine and subaerial erosion is taking place at the cliffs, but it is slow compared to the changes that have taken place in the dunes to the north. The contribution to the sediment budget of the South Haven beaches by sediment derived from cliff erosion is relatively small. The occurrence of chalk pebbles on the southern part of the beach seaward of the

National Trust car park is a good indication that sediments do travel from the southern part of the site. Nevertheless, the main source of sand for the beach appears to be the seabed where there have been extensive sandbanks around the mouth of Poole Harbour throughout the time for which there is a cartographic record.

It remains unclear why there was a sudden onset of dune-building in the 17th century as envisaged by Diver (1933), nor is there any explanation of the wide intertidal area that formed a base for them. The Treswell map shows an earlier sand spit enclosing an inlet that now forms the southern part of Little Sea. The early history of the site is therefore far from clear, despite the detailed historical record. Further investigation is required of both the sub-dune surface and the sedimentation processes in the South Haven area.

One of the rare prograding beaches of southern England, largely nourished by seabed sources of sand, this site has been well documented and its history since the 16th century has been described. A series of sub-parallel dune ridges are the major features. The site also includes low cliffs which were protected by the growth of the dunes at Studland and have since been re-exposed to marine action. The dunes are often quoted as an example of ecological succession, the sequence of dune ridges being characterized by a change inland from dune plants such as lyme-grass *Leymus arenarius* and marram *Ammophila arenaria* to heath species and finally oak scrub. Much of the site is a National Nature Reserve because of its ecological features, but the geomorphological characteristics of the site are a key component. In particular, it is one of the very few east-facing dunes on the English Channel coast.

Conclusions

This site is important because, unusually in southern Britain, it is prograding, and the sequence in which it developed has been well documented. Furthermore, the sediment budget for the beach suggests that much of the sand is derived from offshore, also a relatively unusual feature of beaches in southern Britain. It contrasts with many other British dune systems in lying in an area dominated by offshore winds.

UPTON AND GWITHIAN TOWANS, CORNWALL (SW 575 406)

V.J. May

Introduction

Much of the shoreline of St Ives Bay is formed by dunes, known as the 'Hayle, Upton and Gwithian Towans', banked against and covering bedrock to heights of over 60 m (see Figure 7.1 for general location). Blown sand also covers parts of the western side of Godrevy Point at the northern end of St Ives Bay. Documentary evidence indicates that the dunes spread inland covering small houses from the 12th century onwards (Steers, 1946a). Dunes in the southern part of the site are gradually replaced northwards by rock cliffs, caves, stacks and arches overlain by blown sand and dunes. These features have been exposed as the covering dunes have been eroded and the shoreline has retreated. Remnants of former dunes are still preserved on the stacks, but are gradually being removed by subaerial processes. There has been only limited research on this site (Steers, 1946a; Balchin, 1954; Hosking and Ong, 1963); nevertheless the site is important as an example of a relict cliff coastline. It also allows examination of the interface between the dunes and the sub-dune surface.

Description

The site lies at the northern end of St Ives Bay. It is formed at its southern end (SW 572 043) by active climbing dunes which reach over 25 m in height and at its northern end (SW 580 416) by a series of cliffs, stacks, caves and rocky platforms known as 'Strap Rocks'. Between these two contrasting forms, the dunes undergoing erosion are gradually replaced at the shoreline by a small rock cliff upon which they rest. This cliff reaches about 20 m in height south of Peter's Point before declining towards 15 m around Strap Rocks. Between Peter's Point and the northern boundary of the site (SW 530 417), the cliff is broken by small coves, stacks and caves associated with lines of weakness in the Lower Devonian rocks. The stacks appear to have developed as marine action has attacked joints and other weaknesses (Figures 7.7 and 7.8).

Steers (1946a) described the area as a 'mass

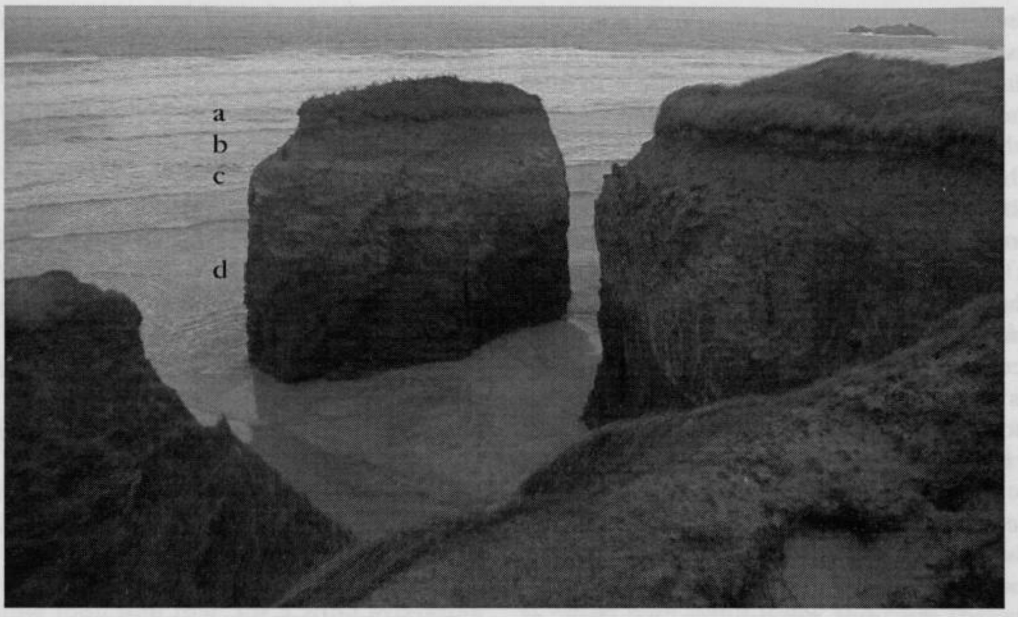

Figure 7.7 Upton and Gwithian Towans GCR site. Both on the mainland and on the stack the sequence a–d is as follows: (a) dune grasses on blown sand; (b) thin sandy soil on weathered clay and angular intermittent gravel-sized clasts; (c) weathered bedrock; (d) bedrock. (Photo: V.J. May)

of high and well-developed dunes', and makes no reference to the erosional forms that now characterize the northern part of the site. Indeed, the dunes have suffered considerable erosion not only since the 1940s but also over a much longer period, for there appear to have been dunes well to seaward of the present shoreline in the early 19th century. Even allowing for the inadequacies of topographical maps as evidence for coastal change (Carr, 1962) both the Ordnance Survey and the Geological Survey maps point to considerable retreat of the shoreline.

Erosion of the rocky coast is slow when compared with the inferred rate of retreat of the dune shoreline. No dating of the interface between the dunes and the surface beneath them has been attempted. Many west coast dunes lie upon a rocky base and often owe their height to their rocky foundations; similar sub-dune rocky cliffs have been observed in Brittany, though without the intricate forms of Strap Rocks.

The dune sands are carbonate-rich (Table 7.3). The beach sands contain both tin and other heavy metals which have presumably been carried to the beach down the streams both to north and south (Hosking and Ong, 1963). The potential fluvial sediment supply to the beach has not been quantified, but may have been significant in the past. De la Beche (1830) indicates that up to 100 000 tonnes a^{-1} was removed from the Camel estuary in the 1820s, and extraction from this area may have removed comparable volumes.

Interpretation

This site is unusual in that it contains both active dunes and intricate erosional forms, the latter exhumed from beneath a retreating sandy shoreline. The relatively rapid changes in this site's cliffed coastline today contrast with the much slower changes farther north at Tintagel. It is the exhumed cliffline that makes this site particularly important for coastal geomorphology. There are several other locations where there is clear evidence of exhumation (Hallsands and Redend Point (South Haven Peninsula) in England, and Tarbat Ness and the Bullers of Buchan in Scotland – see GCR site reports). The dune–rock interface is poorly preserved at Redend Point, whereas in this site it is well exposed. At the Bullers of Buchan (Walton, 1959), stacks and geos are cloaked and infilled by till, indicating that they are at least older than

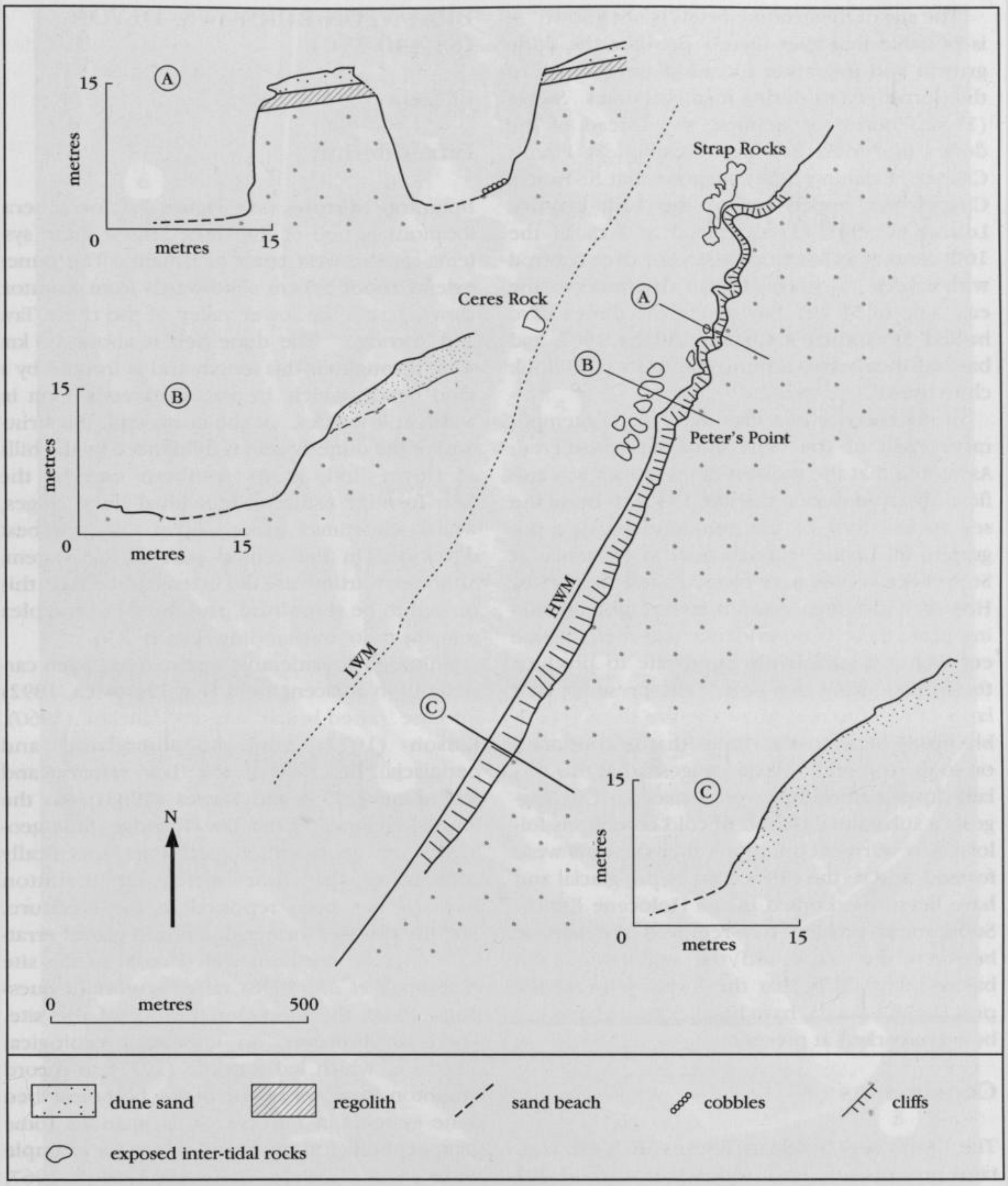

Figure 7.8 Relationships between dunes and cliffs at Peter's Point. Profiles through section A, B and C are shown.

the last glaciation.

Taken as a whole the site demonstrates a sequence from sandy dune shoreline through progressively dominant erosional rock forms to stacks with residual dune deposits atop them. As such, it is a good example of the cyclic nature of the processes affecting the British coastline. Erosional processes were replaced by depositional marine or periglacial processes, the resultant forms then being eroded and the earlier erosional forms exhumed. Even on a shorter timescale of less than 100 years, much of this coastline is marked by oscillation between erosion and deposition.

The age of the exhumed cliffs is not known. It is possible that they merely pre-date the dune growth and migration recorded along much of the Cornish coast during medieval times. Steers (1946a) notes for example the spread of the dunes in Perran Bay that engulfed St Piran's Chapel. Balchin (1954) suggests that St Piran's Chapel was buried before the 12th century. Leland (1535–1543) described St Ives in the 16th century as 'sore oppressed or over covered with sandes…'. Steers (1946a) also refers to 'the east side of St Ives Bay where the dunes have buried St Gothian's Chapel and by 1907 had banked themselves around the walls of Millook churchyard'.

In the absence of a firm date, the contemporary origin of the cliffs must be considered. Assuming that the erosion of the dunes was sufficiently rapid during the late 1940s to bring the sea to the foot of the sub-dune rocky topography, all of the features now in existence at Strap Rocks could have formed since the 1950s. However, although erosion is undoubtedly taking place there is no evidence that the cliffs are eroding at a sufficiently rapid rate to produce the forms during this time. The presence of a layer of regolith and small angular clasts (possibly head) beneath the dunes that is continued on to the top of the stacks suggests that this was laid down before they were isolated. This suggests a substantial period of cold conditions followed by warmer conditions after the cliffs were formed, and so the cliffs could be pre-glacial and have been re-occupied in the Holocene Epoch. Subsequent erosion has removed the surface between the stack and the mainland. On balance it is likely that the forms substantially pre-date the dunes, have been exhumed and are being reworked at present.

Conclusions

The Upton and Gwithian Towans GCR site contains an unusual set of forms that warrant further investigation. Cliff-forms and erosional features are being exhumed at this site from beneath a formerly more extensive dune system. They are unusual within Great Britain because there are few sites where erosional forms are being exposed by the removal of dunes at present. As dunes to the south have been eroded they have exposed former cliffs, caves and stacks.

BRAUNTON BURROWS, DEVON (SS 440 350)

V.J. May

Introduction

Braunton Burrows (see Figure 7.1 for general location) is one of the three largest dune systems on the west coast of Britain. The dunes extend about 6.5 km southwards from Saunton Down across the lower valley of the rivers Taw and Torridge. The dune belt is about 1.3 km wide throughout this length and is fronted by a sand beach, which, in places, exceeds 1 km in width at low tides. At the north end, the structure of the dune system is influenced by the hills of Down End, at its southern end by the Taw–Torridge estuary. Individual dune ridges, which sometimes exceed 30 m OD, are best developed in the central part of the system. Although wartime use did extensive damage, this proved to be short-lived, and the dune complex remains quite outstanding (Figure 7.9).

Although considerable research has been carried out in adjacent areas (e.g. Prestwich, 1892) into the 'raised beach' erratics, Mitchell (1960), Kidson (1977) into the interglacial and periglacial deposits of the Taw estuary, and McFarlane (1955) and Davies (1983) into the 'buried channel' of the Taw–Torridge, little geological or geomorphological data specifically concerning the dune system at Braunton Burrows has been reported in the literature. The presence of former dunes and glacial erratics along the northern cliffed coast of the site (Campbell *et al.*, 1998) raises important questions about the long-term history of the site. There is, however, an important ecological literature, which led Ratcliffe (1977) to record Braunton Burrows as one of the best-described dune systems in Europe. This includes some geomorphological information (see for example Willis *et al.*, 1959a,b; Willis, 1963, 1965, 1967, 1985, 1989; Willis and Jefferies, 1963; Hope-Simpson and Jefferies, 1966; Hewett, 1970, 1971; Hope-Simpson and Yemm, 1979; Hope-Simpson, 1985, 1997; Boorman, 1993). Kidson and Carr (1960) provided a brief summary of the structure of the system in the context of the dune stabilization programme carried out mainly in the central area during the 1950s, and Greenwood (1969, 1978) examined the textural contrasts between the beach and dune deposits.

Figure 7.9 Aerial photograph of dunes and Crow Point. 1, Westward Ho! cobble beach; 2, Taw–Torridge estuary; 3, Crow Point; 4, Airy Point; 5, Braunton Burrows showing main dune ridges and blowthroughs; 6, ridge-and-runnel beach. (Photo: courtesy Cambridge University Collection of Aerial Photographs, Crown Copyright, Great Scotland Yard.)

A number of unpublished reports have been written concerning the aggregate extraction around Crow Point at the mouth of the Taw–Torridge estuary (Figure 7.9). Probably the most relevant in the present context is that by Blackley *et al.* (1972) on the movement of sediment labelled with tracers within the Taw–Torridge estuary area. A review of the geomorphology and management of the Taw–Torridge estuary including Westward Ho! and Braunton Burrows includes details of erosion and sedimentation (Comber *et al.*, 1993)

An extensive programme of topographical surveying of the dunes was undertaken by Kidson and co-workers between 1957 and 1960, during which time the whole dune system was mapped on a scale of 1:2500. Revisions using aerial photography were carried out subsequently. A series of profiles was surveyed across the central and southern dunes annually from 1956 to 1962, primarily to monitor the effects of replanting. Thereafter surveys were less extensive and less frequent because over most of their section-length the dunes had been stabilized. Measurements of blowthrough orientation, and an investigation into the nature and periodicity of the changes in the underlying water-table, were also carried out by Kidson and Hewett, respectively, as part of the work of the Physiography Section of the former Nature Conservancy. Similarly, Kidson and Carr examined the form of the underlying rock surface by means of earth resistivity and refraction seismography, supplemented by boreholes. Very little information concerning these studies has been published. Some maps were produced for the 1964 International Geographical Congress (Kidson, 1964a), but most information remains in the form of partially processed field data. This was remedied to some extent by Kidson *et al.* (1989) who contrasted the earlier surveys with further surveys carried out in 1983, although the description of the dunes that follows is based in part on unpublished English Nature data. Sarre (1989) concentrated specifically on foredune processes and the ways in which they are affected by variations in relief and vegetation.

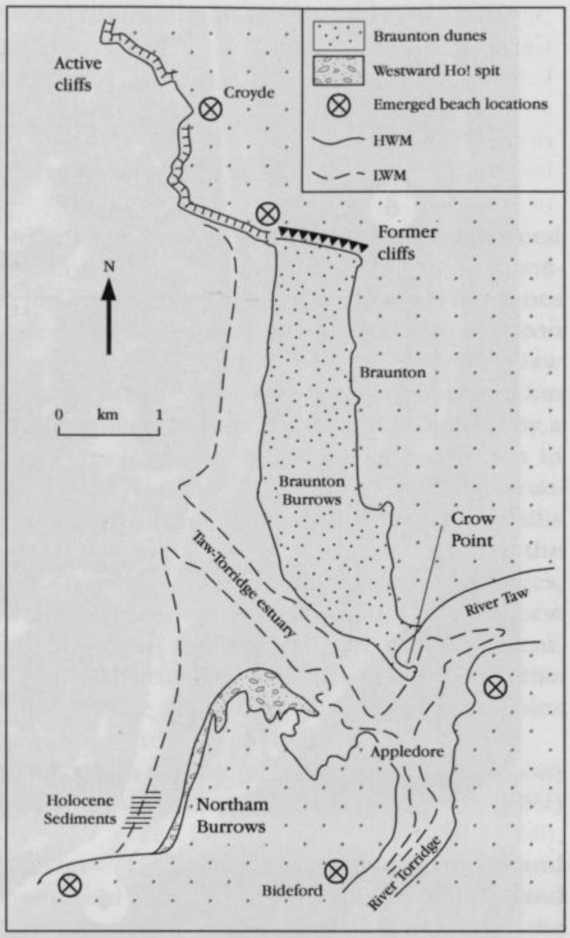

Figure 7.10 Braunton Burrows and Westward Ho! GCR sites, showing locations of emerged beaches and generalized geomorphology. See also Figure 7.11 for photograph of the area around Crow Point.

Description

The dunes at Braunton Burrows are formed mainly of sand with grain size generally between 0.2 mm and 0.3 mm diameter (Willis 1985). They extend from the cliffs below Saunton Down, south for some 5 km to Airy Point (SS 448 330), and thence south-eastwards for a further 1.5 km or so to the narrow strip of land that culminates in Crow Point (SS 466 317; Figures 7.9 and 7.10). In the central area, where the dune structure is best developed, the Burrows consist of three ridges, separated by slacks. The ridges lie parallel to the shore and to each other, within an overall width of about 1.3 km. It is in this area that the highest parts of the dunes occur. In both the north where the dunes abut on to the high land of Saunton Down and in the south, where the shoreline trend changes in response to the Taw–Torridge estuary, the system of three ridges is replaced by a less well-defined double ridge system. Throughout the dunes, but especially in the south, there are a number of sub-ridges perpendicular to the main dune alignment and the coast. They appear to be the legacy of major blowthroughs in the main dune alignments, and may form the northern and southern boundaries of the slacks. There are a small number of parabolic dunes, particularly in the southern part of the dunes (Figure 7.9).

At the rear of the system, there is an extensive area of low dunes and slacks. This is best developed in the central zone; to the south, it becomes narrower, while to the north, it has been modified into a golf course. Both this low area and the slacks elsewhere may be extensively flooded during winter.

For much of its length the seaward dune ridge, usually rising to about 15 m OD, is fronted by a more or less continuous line of foredunes rising to some 4.5 m above OD. The elevation of the slacks is highest in the middle of the central zone of the dunes at about 9 m OD. Towards the north, the surface falls slightly (by the order of 2–3 m) and by rather more at the southern end. There, the lowest slack areas are at approximately 4 m OD, so that if the seaward dune ridges were breached, the slacks would be inundated at high water on spring tides (tidal range being 7.3 m). In the central zone, in particular, slacks nearest the shore are somewhat lower. Willis *et al*. (1959a) observed that the water-table underlying the system was dome-shaped, being some 6 m higher in the centre than at its margins (Figure 7.11). They believed wind deflation took place down to this level. Unpublished work (by D.G. Hewett) shows that the neap-spring tidal cycle can be reflected in the water levels under the dunes for a considerable distance inland.

The central zone of the dunes underwent the heaviest pressure through military usage during World War II, and thereafter. Comparison between maps made by the Ordnance Survey in 1885 and those of the Nature Conservancy produced between 1957 and 1960 indicate major topographical changes over the intervening

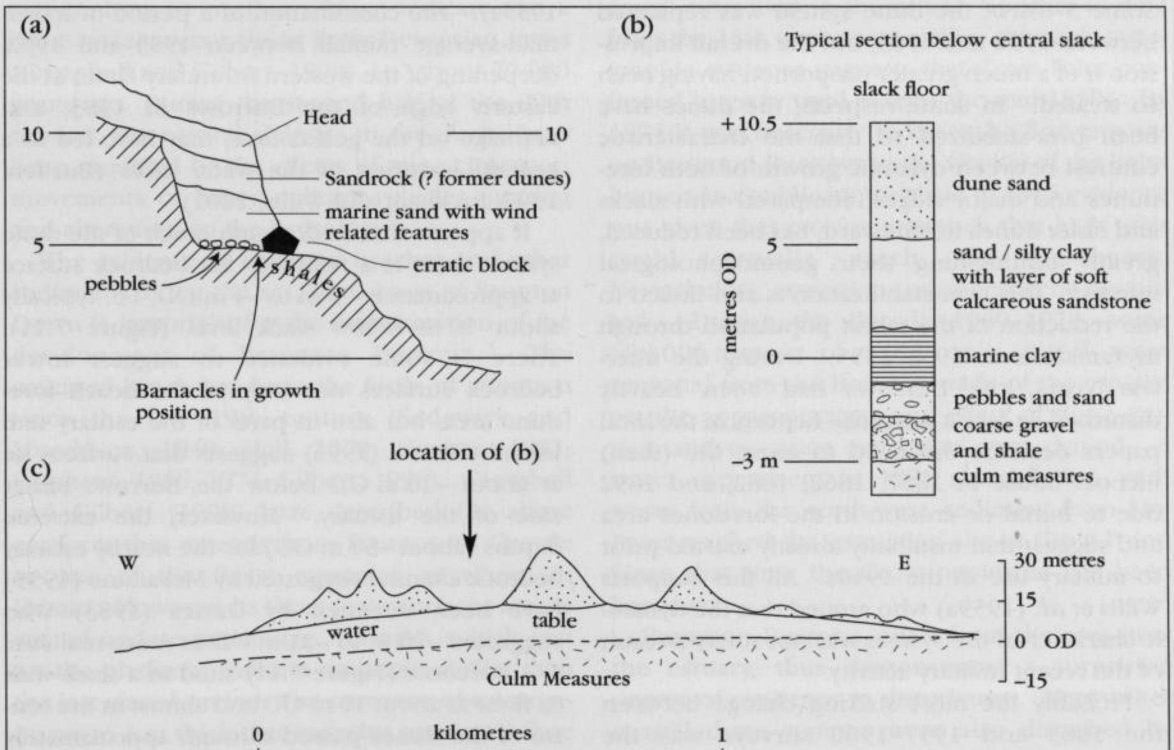

Figure 7.11 Emerged beach profile and dune features at Braunton Burrows GCR site. (a) Section through emerged beach and possible former dunes at Saunton Down; (b) section through the central slack within the main dunes, showing that the dunes lie on both marine clay and gravels and sand resting on the underlying Culm Measures bedrock.; (c) cross-section of the dunes showing the relationship of the slacks to the water table. (Based on Keene 1996; Willis 1985; and Willis *et al.*, 1959a.)

period. These were particularly acute in this central zone where some parts showed an actual inversion of topography with slack areas in 1885 becoming the intermediate ridge of 1957. Mobile dunes continue this process and are encroaching on the slacks at present. Kidson *et al.* (1989) noted that the main dune crest moved eastwards by up to 60 m between 1885 and 1958. Between 1958 and 1983 there was a net gain of sand along the central foreshore, although the source is uncertain.

During the early 1940s, the widespread use of the dunes for military training prior to 'D-Day' (6 June, 1944) caused extensive damage, leaving a 'semi-desert of shifting sand' (Breeds and Rogers, 1998). Furthermore, mine clearance in 1946–1947 was carried out using high-pressure hoses. This destroyed foredunes and rebuilding was encouraged by emplacing brushwood or hessian fencing in the early 1950s. Similar techniques, followed by planting of marram *Ammophila arenaria*, were used to redevelop the middle and landward (main) dune ridge to a more uniform crest height (Hewett, 1970). Some 5–6% of the dune system was replanted between 1952 and 1963, but the overall impression is of a much greater proportion having been so treated. In some respects, the dunes have been over-stabilized so that the characteristic contrast between dynamic growth of both foredunes and major ridges, compared with slacks and older dunes to landward, has been reduced, greatly diminishing their geomorphological interest. This over-stabilization is also linked to the reduction of the rabbit population through myxamatosis in 1954–1955. During the inter-war years, the Burrows had been heavily disturbed by rabbit warrens. Reports in the local papers describe the need to move the (then) lifeboat house in 1857, 1862, 1882, and 1892 due to burial or erosion in the foredunes area and suggest that instability already existed prior to military use in the 1940s. All this supports Willis *et al.* (1959a) who argued that the dynamic character of the system was not solely a result of the recent military activity.

Probably the most striking change between the 1885 and 1957–1960 surveys was the increase in the area occupied by high dunes. It has been calculated that there was a 35-fold increase in the area of land in the central Burrows exceeding almost 30 m OD over that period (Kidson and Carr, 1960), while in the northern third of the system isolated areas topped the 30 m contour for the first time. The more recent survey by Kidson *et al.* (1989) suggests that this trend had continued up to 1983, with the system as a whole having a positive sediment budget.

Willis *et al.* (1959a) describe the contrast in the soils of Braunton Burrows between the highly calcareous (pH 9) high dunes with their low moisture content, and the gley soils of the often far wetter slacks. While the slacks have a somewhat lower pH, they are still alkaline. Plant cover, which depends upon root depth, water availability and nutrient status, strongly affects the likelihood of aeolian erosion. Water availability to plants depends largely on the depth of sand above the water table. During dry periods, sand more than 0.5 m above the water table has a water content less than 5%, but sand within 0.3 cm of the water table is maintained close to saturation and between 0.3 and 0.5 m above the water-table, capillary action maintains moderately high water-content (Willis, 1985). Fluctuations in the level of the water table are strongly correlated with rainfall (Willis *et al.*, 1959a). The combination of a period of lower-than-average rainfall between 1983 and 1992, deepening of the western Boundary Drain at the eastern edge of the Burrows in 1983, and drainage on the golf course, may have led to a general lowering of the water table (Burden, 1997; Packham and Willis, 2001).

It appears that underneath much of the dune system there is a relatively flat bedrock surface at approximately –3 m to –4 m OD, i.e. typically about 10 m below slack level (Figure 7.11). There is some evidence to suggest lower bedrock surfaces not only in the beach–foredune area, but also in parts of the estuary and inland. Keene (1996) suggests that surfaces lie at about –10 m OD below the Burrows either side of the estuary. However, the extreme depths (about –30 m OD) for the nearby estuary bedrock channel suggested by McFarlane (1955) have been disputed by Davies (1983) who suggested –20 m to –21 m OD as more realistic.

A borehole (Figure 7.11) sited in a slack with its floor at about 10 m OD and almost in the centre of the dunes passed through approximately 5 m of sand. Below this level, there were some 4 m mainly of sand, silt and/or clay, but including a 1 m-thick band of soft calcareous sandstone. Underlying these deposits were 2.5 m of marine clay. This, in turn, was underlain by pebbles and sand and then coarse gravel and shale;

less than 2 m in total. Bedrock (Culm Measures) was ultimately reached at –3 m OD. Another borehole located at the extreme northern end of the dune passed through head before reaching a landward extension of the emerged ('raised') beach occurring in the cliff sections of Down End, Saunton. Such cliff sections may show remains of an earlier lithified analogue of the present dune system in juxtaposition to the emerged beach. A coastal platform underlies this feature, which is overlain by head. Kidson (1977) regarded the head as Devensian, the emerged beach as Ipswichian.

Interpretation

The history of Braunton Burrows, both recent and long term, raises a number questions about its origins, its long-term stability, its dynamics and resilience during recent decades of disturbance and the relationships between its ecology, geomorphology and hydrology. Packham and Willis (2001) believe Braunton Burrows to be over 2000 years old, but the Quaternary sediments along its northern fringe indicate that a dune system was here in Early Devensian times (Campbell and Gilbert, 1998), i.e. about 70 000 years ago. During the second half of the 20th century, the natural changes in the dunes have been modified by the effects of mine clearance, movements of heavy military vehicles, grazing and alterations to the hydrology.

The evidence of emerged beaches and other sediments along the southern coast of Saunton Down is important for the interpretation of the development of Braunton Burrows. The emerged beach has been the focus of attention since the late 19th century (Sedgwick and Murchison, 1840; Hall, 1870; Hughes, 1887; Stephens, 1966, 1974; Gilbert, 1996). Campbell and Gilbert (1998) have described the shore platform that extends from Saunton to Croyde as one of the finest examples anywhere in Britain. However, its three main surfaces are, as yet, of undetermined age. Erratics, which rest on the platform, indicate an origin earlier than the last glacial period. The presence of calcarenite up to 3 m thick that includes preserved flute features similar to modern wind-sculpted features in the dunes indicates the presence of earlier dunes banked against the rock slopes (Evans, 1912; Keene 1996). The fact that these possible old dunes are overlain by head (Figure 7.11) supports the suggestion of preservation of interglacial dunes but points to the area having had a similar coastal landscape to that of today. The emerged beach sequence at Saunton has been attributed an Early Devensian age (*c.* 70 000 years BP; Campbell and Gilbert, 1998). In contrast to the southern part of the bay at Westward Ho! (see GCR site report in Chapter 6), there has been only limited description of intertidal submerged forest remnants. Rogers (1946) records that an oak trunk 9 m in length was identified at Braunton Burrows in 1630 (Steers, 1946a). However, there is no record of peat beds being exposed in the seaward edge of the dunes and boreholes through the dunes have not yet proved peat. Dating of the dunes has not yet been possible as a result.

Interpretation of the more recent evolution of the site is mainly dependent upon cartographic evidence from the beginning of the 19th century. These show that over the northern two-thirds of the site the position of the foredunes is substantially the same as it was 150 years ago in spite of post-1945 destruction. However, erosion has occurred near the estuary. Sand and gravel extraction in the estuary appears to date from the 18th century or earlier, although cartographic evidence suggests that Crow Point continued to grow until at least the mid-1850s. By 1874 it was necessary to erect the first groynes on Braunton Burrows in the vicinity of the lighthouse. At a public inquiry held in 1905 evidence was given that erosion was such that high tides could virtually reach the lighthouse. Nevertheless, extraction continued to be permitted. During the decade 1960–1970, some 600 000 tonnes of sand and gravel were removed from the Braunton side of the estuary, yet the apparent cause and effect of dune erosion and estuarine extraction were denied. A tracer experiment in 1971 showed that, with waves from the north-west, sediment from Airy Point reached the extraction site at Crow Point. Since that time the Crow peninsula has been breached.

Braunton Burrows, apart from the area near the estuary, thus demonstrates a surprising degree of resilience to disturbance. Many other coastal dune systems were also disturbed by wartime military activity and post-war mine clearance operations and have also recovered, but in general they were less exposed to onshore winds than Braunton Burrows. Since World War II, the general location and breadth of the beach has changed little suggesting that despite sand migration inland there continues to be some replacement from the nearshore zone (Kidson *et al.*, 1989). The progressive expansion of more woody plants over the dunes has also added to their stabilization (Packham and Willis, 2001). It has been suggested (Packham and Willis, 2001) that the ecological significance of the site depends upon management that encourages an increase in biodiversity and this may be achieved by increased levels of sand movement. Similarly, the geomorphological interest will be enhanced by allowing more dynamism to occur. Even with the extraction at the distal point, and the associated erosion, the dunes as a whole appear to have remained in a positive sediment budget unlike some smaller systems such as Dawlish Warren.

Conclusions

Braunton Burrows is one of the three largest dune systems in western Britain, over 6 km in length, up to 1.5 km wide and attaining heights over 30 m. It is not only one of the largest and most complete dune systems on the coastline of England and Wales, but also unusual in its resilience to serious disturbance and its maintained growth. It is also one of the few such areas where changes in the dune topography have been surveyed regularly. Its ecological importance was recognized in 1964 in its designation as a National Nature Reserve, but lack of grazing decreased its nature conservation interest, and it ceased to be an NNR in 1996. Nonetheless, an agreed experimental programme of grazing was established in 1998 and the site retains its SSSI status; it is a candidate Special Area of Conservation. In terms of geomorphological interest, a conservation policy that allows greater sand mobility within the dunes will only serve to enhance its value as a GCR site.

OXWICH BAY, GLAMORGAN (SS 510 870)

V.J. May

Introduction

Oxwich Bay, on the south coast of the Gower Peninsula (see Figure 7.1 for general location) supports a well-developed system of dunes. As at Pwll-ddu, to the east (see GCR site report in Chapter 8), the beach and dunes have diverted a small stream towards the east. Oxwich Bay includes part of the Oxwich Burrows National Nature Reserve (NNR), a wetland site behind the dunes, but its main geomorphological interest lies in the association of the dunes with bounding cliffs which restrict the transport of sediment into and out of the bay and modify the behaviour of waves within the bay. Research has concentrated mainly on the Quaternary deposits that rest at the foot of the coastal slopes and cliffs (Campbell and Bowen, 1989), and demonstrates that this cliff is mainly a Pleistocene relict feature variously reworked along its foot during the Holocene Epoch.

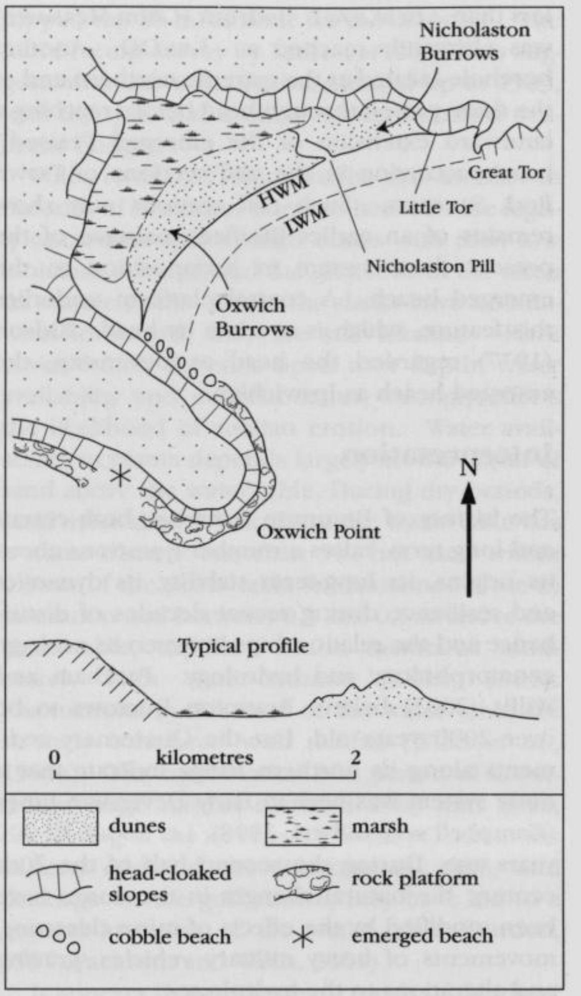

Figure 7.12 Key geomorphological features of Oxwich Bay, together with a typical profile.

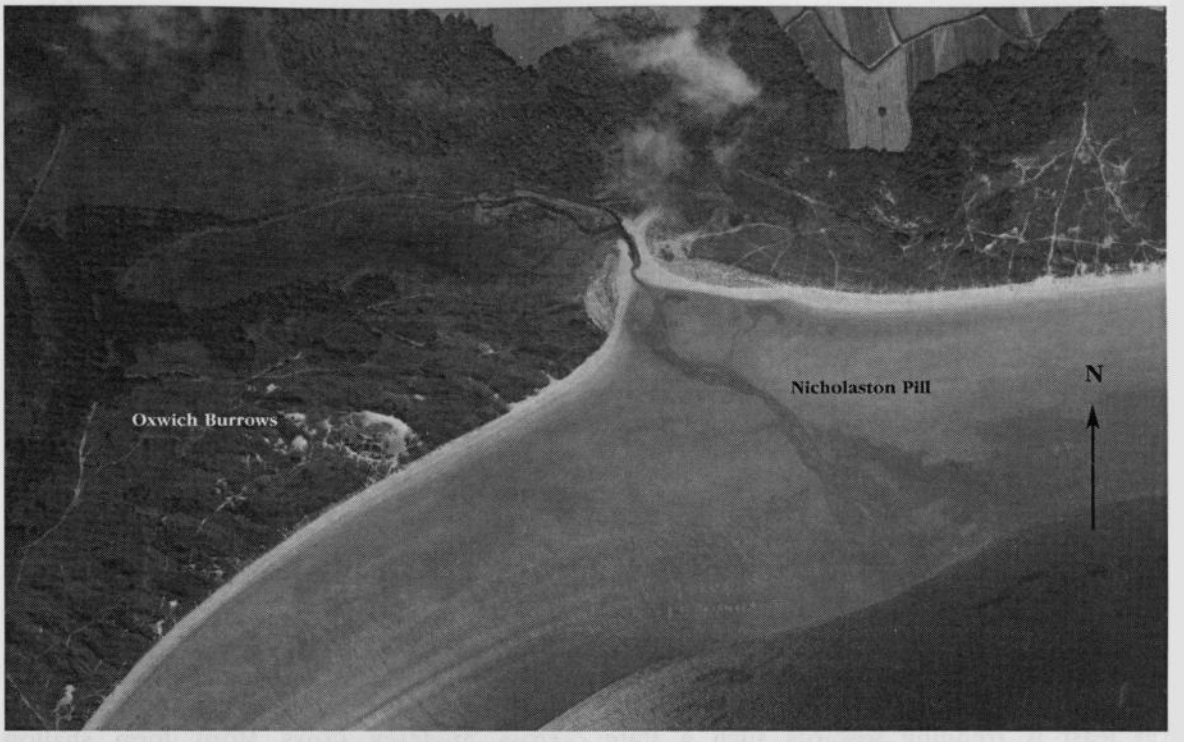

Figure 7.13 Oxwich Burrows. Linear dune ridges are evident, with alignment close to right angles to the shore at the western end of the dunes. Towards the east, the ridges retain this orientation close to the shore, but have a more east–west alignment inland. Similar ridges are absent from the dunes east of the stream mouth. (Photo: courtesy Cambridge University Collection of Aerial Photographs © Countryside Council for Wales.)

Description

The site lies between Great Tor (SS 530 876) in the east and Oxwich Point (SS 513 850) in the west. The re-entrant form of the bay is controlled by a syncline in Namurian strata aligned north-west–south-east. There are three main landforms (Figure 7.12).

1. An area of dunes that rests against slope-over-wall cliffs in Nicholaston Burrows and between Little Tor and Great Tor. At the extreme eastern end of the site the cliffs, over 60 m in height, fall directly to an active beach.
2. A single major dune system, Oxwich Burrows, and an intertidal sandy beach, backed by scrub and saltmarsh.
3. Cliffs, mainly of slope-over-wall type, between Oxwich Point and Oxwich Castle. Only the lower part of the cliff, the 'wall' and shore platforms have been included in the site.

Largely sheltered from the main energy of waves approaching the Gower Peninsula from the south-west, the beach in Oxwich Bay swings from a east-south-easterly aspect at its southern end to a southerly aspect at its more exposed eastern end. The beach extends eastwards beyond Great Tor at low tide into Three Cliffs Bay. The dunes are crossed by a small stream, Nicholaston Pill, which drains marshland behind the dunes. It is likely that sand moves out of the bay towards the east at low tide, especially when wave energy is high. Since the dunes remain, this implies that there is a balancing supply from offshore. The shallowness of the bay (mainly less than 10 m in depth), and the unidirectional wave energy at the beach also serves to enhance the sand supply to Oxwich Bay.

Interpretation

The generally accepted history of the site (Ratcliffe, 1977) suggests that the main beach ridge developed about 2500 years BP enclosing a brackish lagoon. This was land-claimed during the 16th century and, subsequently, fish-ponds were dug in the wetlands behind the dunes. Since the formation of the ridge, the dunes appear to have been stable, even growing in extent. Sufficient sand has accreted to fill the area of Nicholaston Burrows on the eastern side of Oxwich Bay, most of which was probably a rocky coast when the ridge was first formed. To the west of this site, the 60 m coastal platform is truncated seawards by a relict cliff, which is partially buried by superficial deposits (Campbell and Bowen, 1989). A shore platform cut in Carboniferous Limestone at about 10 m OD forms the lower part of the slope. At Nicholaston Burrows, the slopes have a similar upper form, but the lower slopes are masked by the dunes banked against them. This is the only substantial length of former cliffed coast on the southern side of the Gower Peninsula that is protected in this way by dunes.

This is undoubtedly a beach that has had a positive sediment budget until recently. The increased recreational use of the dunes during the last three decades has brought about much localized erosion, associated with trampling and blowthroughs. The erosion of the frontal dunes might suggest that the whole site is in deficit or at least is trending towards such a state. However, a brief consideration of the sediment budget of the site suggests that this is not likely, when the whole bay is considered. First, there is only a limited possibility for longshore transport of sediment out of the beach. Second, sand is transferred within the site, either by wind or by waves so that erosion in part of the beach and dune area appears to be balanced by deposition elsewhere. Third, this beach could be expected to act like other bay-head beaches that lie in locations where waves are strongly refracted during their approach towards them.

Unfortunately, the most vulnerable part of the shoreline is the main point of access to the beach. Most trampling occurs at the most likely point for erosion. Sand is transferred mainly from beach to dunes and *vice versa*, but because the total volume of sand is limited the dunes have been constrained both in height and in their growth seawards. Equally there has been no tendency for the dunes to migrate inland since they are largely stable.

Conclusions

Oxwich Bay is a structurally controlled bay within which nationally important dunes have developed despite restricted longshore sediment sources. It had, until very recently, a positive sediment budget, unlike many beaches worldwide. Trampling of the dunes by visitors appears to have led to instability, hence its current tendency for erosion at its western end. Its sheltered, low-energy, environment has allowed the growth of low – but nationally important – dunes, despite a restricted sediment input. The combination of a low-energy beach in a macrotidal setting, relict cliffs against which it is banked, its bay-head location and the biologically important but restricted dunes make this a nationally important site. It is an important member of the national GCR network of bay-head beaches.

TYWYN ABERFFRAW, ANGLESEY (SH 362 685)

V.J. May

Introduction

Many of the structurally aligned valleys that cross Anglesey (Ynys Môn) form shallow estuaries on the south coast, including the largest, the Afon Cefni, which lies within the Newborough Warren GCR site (see site report in Chapter 11). Tywyn Aberffraw comprises a small beach and area of dunes, which lie to the west of the much larger dunes of Newborough Warren, and occupy a confined valley site (see Figuer 7.1 for general location). Because of the physical constraints of the locality, there is little possibility of sand entering or leaving the bay alongshore, and the bounding cliffs supply very little sediment to the beach (Robinson, 1980b). Tywyn Aberffraw provides an excellent opportunity for the study of beach and dune relationships within an area of restricted sediment supply. The site is also distinguished by the relative isolation of individual fixed parabolic dunes upon a sand plain (Steers, 1946a; Ranwell, 1955; Robinson and Milward, 1983). This landform assemblage has few comparable equivalents in Britain.

Description

Tywyn Aberffraw is a small site, with a beach only 700 m wide between hard-rock headlands, but the sand plain and dunes extend about 2.5 km inland (Figure 7.14). The site fills the western end of Traeth Mawr, one of several low-lying basins that cross Anglesey from south-west to

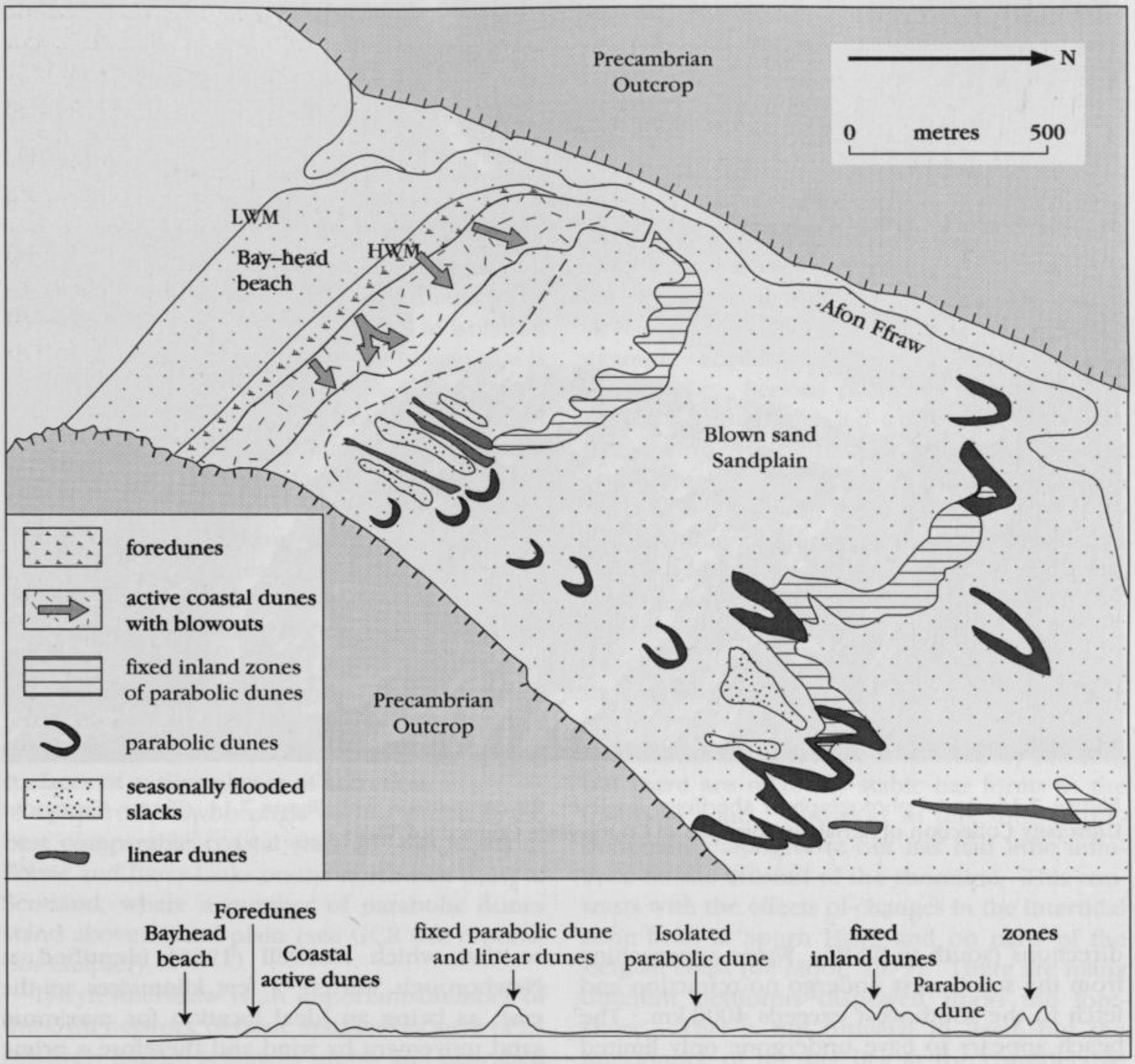

Figure 7.14 Key geomorphological features and profile of the Tywyn Aberffraw GCR site. (After Robinson and Milward, 1983.)

north-east and cut here into the Precambrian grits, shales and lavas of the Gwna and Fydlyn groups. The valley is filled at its south-western end by sand, almost all lying within the rocky confines of the valley, but there has been very little migration of sand on to the higher rocky surfaces on either side. Broadly, the site falls into four morphological units: the cliffs, the beach (swell-aligned towards the south-west) the active dunes, which form a triangular area less than 250 m wide at the western end of the beach but widening to about 1 km along the eastern boundary of the site, and the sand plain and mainly fixed dunes that form most of the site.

The cliffs form low (rarely more than 7 m) vertical features cut into the Precambrian rocks, above which there are more extensive slopes rising to about 40 m OD. These slopes bound the site on both sides, with a small stream, the Afon Ffraw, flowing at the base of the western slope. Although the slopes are not included within the site, they have confined sand to the valley floor and provide some shelter from winds from the west and east. The beach is about 300 m wide at low water and is composed almost entirely of sand. Waves can only approach the beach from a very narrow range of

Figure 7.15 Aerial photograph of Aberffraw, Anglesey, for comparison with Figure 7.14. (Photo: Cambridge University Collection of Aerial Photographs © Countryside Council for Wales.)

directions (south to WSW). Waves approaching from the south-west undergo no refraction and fetch to the south-west exceeds 4000 km. The beach appears to have undergone only limited retreat in recent decades. The active dunes are affected by some recreational trampling and are eroded periodically by wave action. Wind action carries sand along the eastern side of the site, while on the western side the Afon Ffraw it prevents accumulation along the foot of the bounding slope. The western slope is, however, also sheltered from the strongest winds. As a result, along the eastern edge of the site the active zone extends almost 1 km inland. The main part of the site is dominated by a sand plain that slopes from over 14 m OD in the east to about 8 m OD in the west. Several isolated vegetated parabolic dunes rise above the sand plain, one of the best examples being at SH 367 694.

Interpretation

This site occupies a similar position on the coast to that which Ranwell (1955) identified at Newborough Warren, a few kilometres to the east, as being an ideal location for maximum sand movement by wind and therefore a prime site for the study of dune development and migration. Unlike Newborough Warren, the beach at Tywyn Aberffraw is extremely restricted laterally with limited sand removal by longshore drift. The beach retains an almost constant orientation because the adjacent headlands restrict the direction of wave approach. As a result, this can be described as 'an almost perfect bay-head beach' (Robinson, 1980b, p. 42) for which the offshore zone is the most likely source of sediment for the accumulating beach. In turn the dunes rely entirely on the supply of sand from the narrow beach and some recycling by the stream. The restriction of the site between higher ground has also affected the patterns of wind transport because the western side is more sheltered from westerly winds and the valley widens away from the beach. The sand available for maintenance of dunes, which are migrating inland, is therefore limited both in quantity and in its spatial distribution. However, the site is grazed by sheep, cattle and rabbits (Ashall *et al*., 1995; Potter and Hosie, 2001), which may affect sand mobility locally. Unlike Newborough Warren, where there is a tendency for linear dunes to migrate inland (Ranwell, 1955), dunes at Tywyn Aberffraw tend to be isolated and lower. This is almost certainly a result of a limited sediment input and a minimal longshore supply. Parabolic dunes stand in isolation above the plain in a landform assemblage that is uncommon in England and Wales.

The internal structure of one of the largest parabolic dunes consists mainly of landward-dipping accretion surface, both on the windward (foreslope) and the leeward (rearslope) of the dune (Bristow and Bailey, 2001). A large area of trough cut-and-fill identified by ground-penetrating radar on both the windward slope and the dune crest indicates that sediment is being moved from the windward side and transported to the leeward side. As the dunes migrate landwards, they preserve some of the older landward-dipping surfaces of earlier phases of accretion.

Apart from Newborough Warren, probably the best comparable coastal sites are the Sands of Forvie and Barry Links on the north-east coast of Scotland, where a number of parabolic dunes stand above a sand plain (see GCR site reports, this chapter).

Tywyn Aberffraw is an important member of the GCR network of dune systems because of its relatively limited sediment supply and restricted development of dunes. In this respect it contrasts especially strongly with its neighbour at Newborough Warren.

Conclusions

Tywyn Aberffraw is an almost perfect geomorphological exemplar of a bay-head beach that is backed by dunes that include probably the best example of a sand plain with isolated parabolic dunes in England and Wales. The site combines the unusual attributes of a near-perfect sandy bay-head beach and a sand plain with isolated parabolic dunes. Furthermore, its continued development can be shown to depend almost exclusively upon offshore sand sources and fluvial recycling rather than any longshore sediment transport.

AINSDALE, LANCASHIRE (SD 285 105)

V.J. May

Introduction

Much of the coastline of Merseyside and Lancashire is dominated by dunes and very wide intertidal sand and mudflats, but it has also been developed as residential areas and/or resorts, for example Formby, Southport, Blackpool and Morecambe. Serious problems of erosion and coastal flooding have led to parts of the shoreline being strengthened by sea-walls and embankments, and many of the original dune areas have also been damaged or destroyed by afforestation and urbanization. Ainsdale is a National Nature Reserve primarily because of its important dune flora and fauna, but it also includes features of considerable geomorphological importance; predominantly its dunes and the multi-barred ridge and runnel foreshore (see Figure 7.1 for general location).

Much of the shoreline is affected by erosion, but there are relatively stable bar forms in the intertidal zone. Transport in this zone is predominantly alongshore but has had little influence on the erosion of the shoreline. This contrasts with the effects of changes in the intertidal zone both at Spurn Head and on parts of the Belgian coast (de Moor, 1979). There are many different bedforms displayed upon the foreshore. This is not unusual in itself, but the importance of the site lies in the considerable research that has been carried out. In this respect, it offers an excellent opportunity for comparisons with the sandy shoreline at Gibraltar Point (see GCR site report in Chapter 8) which also lies in a macrotidal environment, but which has a different wave climate.

This coastline was the focus of one of the first regional coastal monographs (Ashton, 1920). Its importance in studies of the evolution of the coastline has been continued to the present time (e.g. Gresswell, 1937, 1953a,b, 1957; Tooley, 1974, 1976, 1978, 1982; Parker, 1975; Kidson and Tooley, 1977; Bird, 1985; Bird and Schwartz, 1985; Innes and Tooley, 1993). In addition, considerable attention has been given to the forms and processes of the intertidal areas and the dunes (e.g. Sly, 1966; Parker, 1971, 1975; Wright, 1976, 1984; Pye and Smith, 1988; Pye, 1990, 1991; Pye and Neal, 1993, 1994; Pye *et al*., 1995). Unlike many other coastal geomorphological sites, there is also a substantial history of detailed oceanographic investigation in the offshore area (Darbyshire, 1958; Bowden, 1960, Murthy and Cooke, 1962; Lennon, 1963; Lennon, *et al.* 1963; Halliwell and O'Connor, 1966; Belderson and Stride, 1969; Draper and Blakey, 1969; Ramster and Hill, 1969). Its ecology is summarized in Atkinson and Houston (1993) and Smith (1999). Hansom *et al.* (1993) reviewed the dune morphology in the context of general erosion and sedimentation patterns in the Ribble estuary area.

Description

The site falls into eight zones (Figure 7.17a) described below as a seaward transect (Parker, 1975):

1. Inland the site is dominated by extensive largely stable dunes that rise to over 23 m OD. Many of the ridges are aligned east–west and generally reach about 16 m OD. Although there are hummocky dunes, true parabolic dunes are poorly developed.
2. To seaward, the dunes are characteristically aligned with the shoreline in a belt up to 200 m wide. They are separated by narrow slacks.
3. An active eroding dune zone up to 80 m in width. Blowthroughs (Parker, 1975), some of which form deep gullies, affect the local movement of sand inland. Damage by trampling also occurs.
4. A narrow, upper foreshore plane area described by Parker (1975) as 'a planar seaward-sloping zone lying between the most landward runnel and the sand dunes at high water mark'.
5. A zone of ridges and runnels, including as many as four ridges, 0.5 m to 1.2 m in height.
6. A lower foreshore formed mainly by intertidal sandflats, which is terminated by a low-water berm.
7. A subtidal slope.
8. Sublittoral sand ridges, 0.5 m to 1.0 m in height with a wavelength of 300 m to 500 m.

Pye (1990) recognized three phases of dune development:

1. Before 1800 – irregular hummocky dunes with incipient blowthroughs and parabolic dunes. These are fed by a positive beach sand budget, and with incomplete vegetation cover, prograde gradually seawards.
2. 1880–1906 – a series of dune ridges parallel to the coast were produced by a positive beach-sand budget and sand-trapping vegetation provided by brushwood fencing and marram *Ammophila arenaria* planting. The dunes vary from mobile to semi-fixed, and embryo dunes are still developing where beach accretion occurs.
3. Post-1906 – erosion around Formby Point and disruption of the vegetation cover produced large transgressive sand sheets. These result (Pye, 1990) from: (a) little resistance by vegetation to blowthrough development or to sand encroachment on a broad front; (b) the large directional variability of wind, and (c) the limited development and maintenance of high dunes at Formby because of heavy pedestrian-pressures.

This is a macrotidal environment, with a range at high spring tides of 8.2 m. Occasional surges raise the level of high water (Lennon, 1963). Maximum local waves occur with strong south-westerly to north-westerly winds. The most common waves have a significant wave height of 0.6 m to 1.0 m and a period of 4.0 s to 4.5 s (Parker, 1975). The highest waves may exceed 9.0 m (Murthy and Cook, 1962; Draper, 1966). Pye (1990), however, suggests that severe storm waves with period 8 to 7 s do not exceed 5.7 m in height. The intertidal slope is about 1:244. The dunes include both active and stable areas, though they are generally more stable inland. This stability is reflected in a soil chronosequence that culminates in podzols under sandy heath at Freshfield (Kear, 1985). Slacks are affected by high water-tables. Ranwell (1972) noted that a slack dominated by a mosaic of semi-aquatic plant communities described by Blanchard in 1952 was being threatened by erosion of the dunes on its seaward side. As a result of such changes in the dune morphology, former slack deposits appear from time to time on the foreshore. Fossil dune slacks have been identified on Formby foreshore (Tooley, 1976). Holocene silts and clays underlie the foreshore and affect the drying and wetting of the sand ridges. They are commonly exposed in the runnels. At Downholland Moss marine transgressive and regressive overlaps were dated to 6890

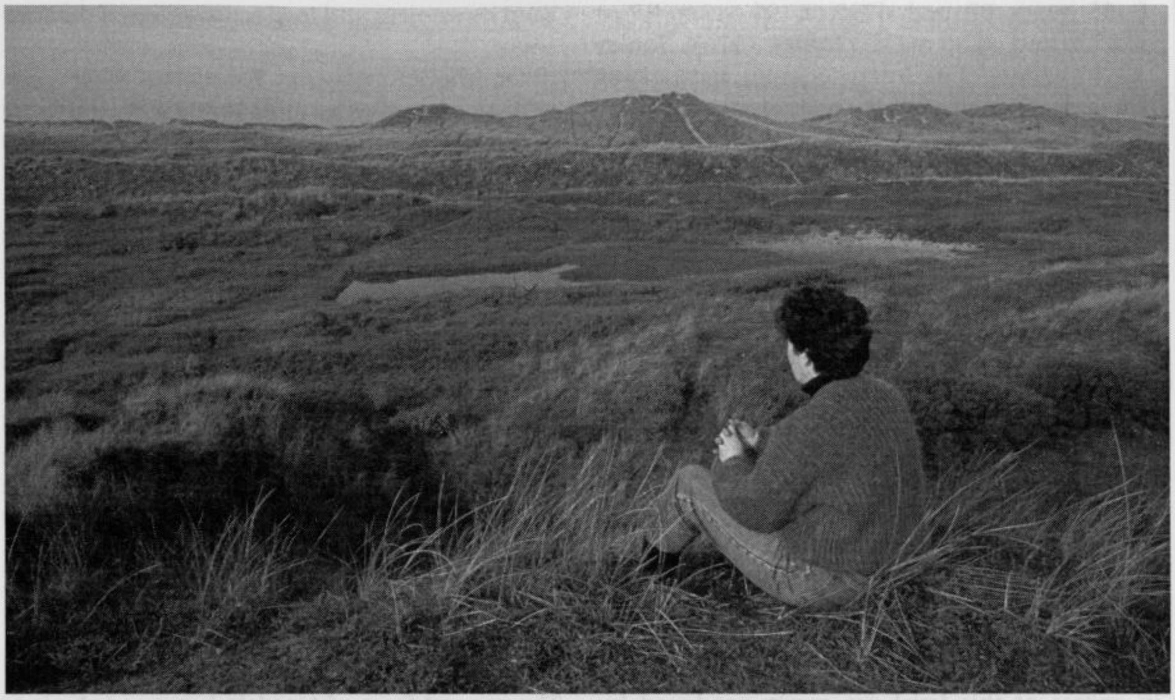

Figure 7.16 Ainsdale National Nature Reserve, view looking towards the west, North of Fisherman's Path. The site important for geomorphology (it is one of the three largest dune systems of the west coast of England and Wales) as well as for wildlife. In the middle distance a 'toadscrape' has been created to encourage natterjack toads. (Photo: copyright English Nature.)

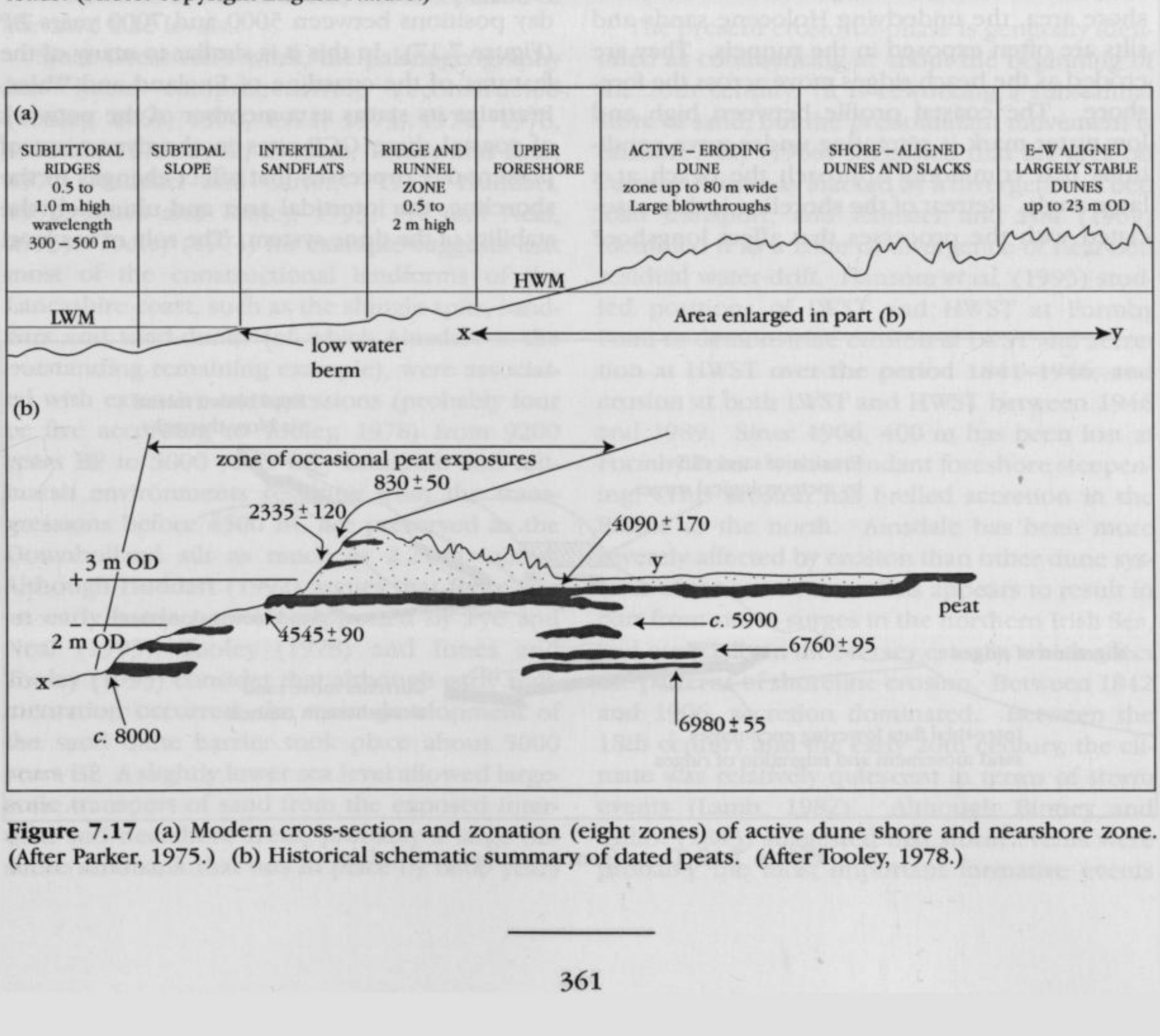

Figure 7.17 (a) Modern cross-section and zonation (eight zones) of active dune shore and nearshore zone. (After Parker, 1975.) (b) Historical schematic summary of dated peats. (After Tooley, 1978.)

± 55 years BP and 6790 ± 95 years BP at –0.87 m and –0.36 m OD (Tooley, 1976). Tooley (1978) refined this interpretation, recognizing five periods of marine transgression designated as Downholland I–V, with radiocarbon dating of key horizons as index points for sea level (Tooley, 1978).

Parker (1975) described the main processes working on both the active dunes and the foreshore. Only limited sand from the foreshore is fed directly to the dunes because even though the ridges dry, blowing sand cannot reach the dunes where the runnel between the most landward ridge and the plane area remains wet at all times. Landward sand movement from the ridge and runnel zone to the dunes is blocked. Sand is blown from the plane area along the face of the dune cliff to travel inland along the gaps in the ridge. Erosion of the sand cliff is strongly associated with wave undercutting (Figure 7.18). Most rapid retreat occurs when tides exceed +5.2 m OD. Lennon (1963) showed that tides in excess of this level are rarely produced by undisturbed astronomical tides, and so most erosion of the sand cliffs appears to be associated with storm surges at high water. In the foreshore area, the underlying Holocene sands and silts are often exposed in the runnels. They are eroded as the beach ridges move across the foreshore. The coastal profile between high and low-water mark is retreating under wave conditions that commonly approach the beach at a large angle. Retreat of the shoreline is thus associated with the processes that affect longshore sand movement and lead to lowering of the foreshore.

On the multi-barred foreshore, waves and tidal streams are the most important sources of energy for the movement of sediment, together with the abundance of sand and the influence of the short fetch on wave length. Breakers are dominant on the ridges, whereas currents (both wave-induced and tidal) predominate within the runnels. Sediment transport is predominantly alongshore within the runnels, but there is only limited movement onshore. Parker (1975) commented on the lack of understanding of the role of mud in processes of sub- and intertidal sedimentation. He found little evidence to support the suggestion (Robinson, 1964) that some channels are dominated by ebb flows in contrast to others that are dominated by flood-tide flows.

Interpretation

The general form of Ainsdale has come about as a result of progradation associated with sea-level rise. Sea floor deposits of sand were gradually transported landwards to broadly their present-day positions between 5000 and 7000 years BP (Figure 7.17). In this it is similar to many of the features of the coastline of England and Wales. It attains its status as a member of the network of coastal dune GCR sites in the dynamism of present-day processes that affect changes in the shoreline, the intertidal area and ultimately the stability of the dune system. The role of sea-level

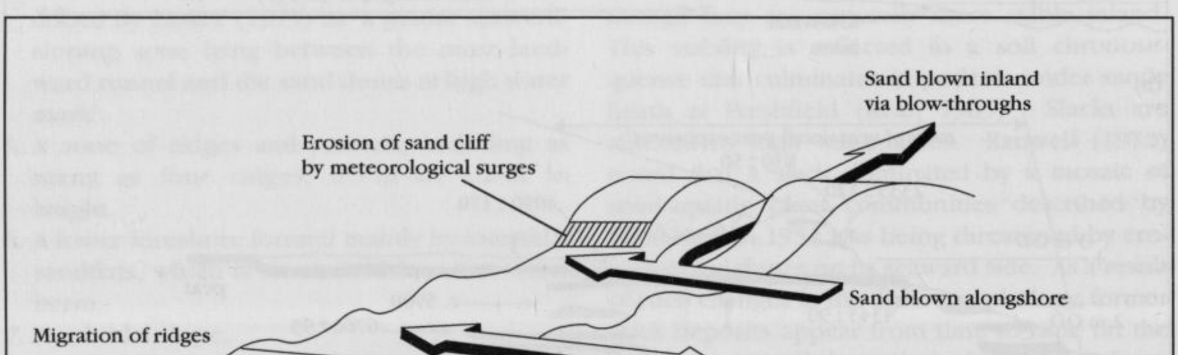

Figure 7.18 Dune-front processes at Ainsdale.

change, the development and breaching of coastal barriers and progressive sedimentation have been the subject of local reports since the 17th century (Binney and Talbot, 1843; de Rance, 1869, 1872, 1877, 1878; Reade, 1872, 1881, 1902, 1908). During the early 20th century there were many studies of the biogenic sediments (Travis, 1908, 1922, 1926, 1929; Erdtman, 1926; Blackburn in Cope, 1939) and the stratigraphical record (Cope, 1939; Wray and Cope, 1948; Hall, 1954–1955). Gresswell (1937, 1953a,b, 1957, 1964) developed a model of coastal evolution based on an initially low sea level about 18 000 years BP followed by rapid sea-level rise to about 5000 years BP. Subsequent glacio-isostatic uplift caused the shoreline to retreat westwards and the sandy coast developed as a regressive wedge (Gresswell, 1953a). Gresswell (1953b) identified the former coastline of southern Lancashire at about +5.2 m OD, his 'Hillhouse Coast', but this was rejected by Tooley (1978) who argued that evidence for this former coastline was seriously flawed. Tooley (1976) showed that in the Martin Mere basin, the 'Hillhouse' coastline is not related to a marine event, but to a period of elevated lake levels.

Since Gresswell's work, the palaeogeography has been comprehensively reconstructed (Tooley, 1969, 1970, 1971, 1973, 1974, 1976, 1977a,b, 1978, 1982, 1985a,b; Tooley and Kear, 1977; Huddart and Carter, 1977; Huddart, 1992; Innes and Tooley, 1993; Pye and Neal, 1993). Tooley (1974) for example suggests that most of the constructional landforms of the Lancashire coast, such as the shingle spits, sandbars and sand-dunes (of which Ainsdale is the outstanding remaining example), were associated with extensive transgressions (probably four or five according to Tooley, 1978) from 9200 years BP to 5000 years BP. Estuarine and saltmarsh environments resulting from the transgressions before 4500 BC are preserved as the Downholland silt as much as 2.2 km inland. Although Huddart (1992) argues that there was an early barrier, a view supported by Pye and Neal (1993), Tooley (1978) and Innes and Tooley (1993) consider that although early sedimentation occurred, the main development of the sand dune barrier took place about 5000 years BP. A slightly lower sea level allowed large-scale transport of sand from the exposed intertidal and nearshore areas, probably a large offshore sandbank that was in place by 6800 years BP (Pye and Neal, 1993), to form the dunes. The seaward edge of Downholland Moss (now about 4 km from the coast) was covered by sand about 4090 ± 170 years BP (Tooley, 1978) and peat deposits at Sniggery Wood were probably buried about 4510 ± 50 years BP (Figure 7.17). 'Fossil' dune slacks or peat exposed within the beach have been dated (for example the former at Formby dated at 2335 ± 120 years BP and 830 ± 50 years BP: Tooley, 1978; Innes and Tooley, 1993 and the latter at Alt Mouth at 4545 ± 90 years BP and below low tide level dated at about 8000 years BP: Tooley, 1978). Innes and Tooley (1993) summarize the pattern as follows:

1. An initial period of sand migration and dune-building between 4600 and 4000 years BP.
2. After several centuries of sand migration, a coastal dune in place by 4000 years BP.
3. Continuing sand accumulation interrupted by marine transgressions about 3500, 2335, 1795–1370 and 800 radiocarbon years BP.
4. A recent erosional phase.

The present erosional phase is generally identified as commencing at about the beginning of the 20th century. It is reworking a substantial store of sand, but the predominant movement is offshore. Sly (1966) suggested that the area off Formby Point was marked by a divergence of bed load transport, and Ramster and Hill (1969) identified it as a zone of divergence of near-bed residual water drift. Hansom *et al.* (1993) studied positions of LWST and HWST at Formby Point to demonstrate erosion at LWST and accretion at HWST over the period 1841–1946, and erosion at both LWST and HWST between 1946 and 1989. Since 1906, 400 m has been lost at Formby Point with attendant foreshore steepening. This erosion has fuelled accretion in the Ribble to the north. Ainsdale has been more severely affected by erosion than other dune systems of the west coast. This appears to result in part from storm surges in the northern Irish Sea, and especially in the Mersey estuary, which affect the patterns of shoreline erosion. Between 1842 and 1906, accretion dominated. Between the 18th century and the early 20th century, the climate was relatively quiescent in terms of storm events (Lamb, 1982). Although Binney and Talbot (1843) suggested that storm events were probably the most important formative events for the evolution of this coast, sea-level rise has until recently been the more favoured explanation (Pye, 1991, 1992). Plater *et al.* (1993) however, demonstrate that storm surges have played a critical role in the erosion of the dune frontage and also in the sediment transport dynamics of the Formby–Ainsdale coast (Figure 7.18). Since about 1900 the whole frontage of about 5 km has been eroded by up to 3 m a^{-1} (Pye and Neal, 1994). However, single storm events can cause the dunes to retreat between 6 and 14 m (Pye, 1991). The high frequency of strong westerly winds has been a factor, but the construction of training walls and the dumping of spoil offshore has also played a role by focusing wave energy onto the north-central part of Formby Point (Pye and Neal, 1994).

The site is well known for its many smaller-scale features in the intertidal area, and has been the key site in Britain for the description and interpretation of ridge and runnel forms. The coastline at Blackpool and Ainsdale to its south were the location of extensive studies into the interpretation of aerial photographs prior to the Normandy landings in 1944 (Williams, 1947; King and Williams, 1949). At this time, King developed her swash-bar interpretation of ridge and runnel on equilibrium-seeking beaches, which was further elucidated in 1972 and 1982. Wright (1976) and Orford and Wright (1978) showed that, on the basis of detailed studies at Ainsdale, ridges and runnels as quasi-stationary features resulting from swash processes could be distinguished from breakpoint bars and troughs associated with breaking waves. More recently, Orme and Orme (1988) have argued that three models for ridge and runnel formation can be identified:

1. Swash-bar deposition of ridges. This follows King's (1959) model, but is most common in macrotidal areas.
2. Ridges and runnels result from the onshore migration of longshore bars and troughs.
3. Runnel erosion rather than ridge accretion can also occur. This appears unlikely at Ainsdale because of the role of the muddy subsurface in sand movements.

The contrast between the shore-parallel dune ridges and the west–east alignment of dune ridges farther inland suggests that the role of blowthroughs is important. As these semi-mobile dunes become stabilized by vegetation, they become fixed features of this landscape. A specific issue that warrants further research is the extent to which this fixed linearity is established with the development of each new seaward ridge and its associated slack.

Conclusions

Ainsdale is a nationally significant site in that the development of this extensive dune system depends upon not only long-term changes during the Holocene Epoch, but also on the detailed effects of surges, sand movements and especially the ridge and runnel of its multi-barred foreshore; it could be regarded as the type area for such forms in Britain. Ainsdale greatly increases our understanding of coastal processes and their relative roles at many different time and space scales. The detailed interpretation of the Holocene history means that this site is of international significance for understanding of the effects of changing sea levels during the Holocene Epoch. In addition, the detailed monitoring of the site provides a nationally important location for the development of strategies for coastal management in the face of global climate change.

One of the three largest dune systems of the west coast of England and Wales, Ainsdale is a National Nature Reserve because of its dune flora and fauna, but its coastal geomorphological interest is considerable. The place of Ainsdale in British coastal geomorphology is very significant, for research has focused on both the present-day processes and the changes during the Holocene Epoch and it provides a key site for interpretation of coastal change in north-western England.

LUCE SANDS, DUMFRIES AND GALLOWAY (NX 150 555)

J.D. Hansom

Introduction

Luce Sands represents an exceptional assemblage of dynamic coastal landforms and contains examples of both contemporary and Holocene marine features. In this respect, it is similar to the GCR sites of Culbin, Morrich More and Spey Bay in the north-east of Scotland (see GCR site reports in Chapters 11 and 6).

Luce Sands

Luce Sands is the largest and most complex system of beach and dunes in the south of Scotland and the juxtaposition of landforms are unique to this site. The geomorphological interest of Luce Sands and the reasons for its selection for the GCR include a series of Holocene emerged gravel ridges, the extensive, complex and dynamic dune system of Torrs Warren overlying the gravel ridges and the diversity of the contemporary coastal features. The relatively large size of the 'soft' coastal landforms would be of interest purely as static landforms, but the highly dynamic nature of the beach system imparts especial interest. Additionally, the ongoing accretionary processes at Luce Sands (Mather, 1979; Single and Hansom, 1994) identify this site as one of few in Britain (and a minority on an international scale) that displays long-term progradation.

Description

Luce Bay is situated to the south of Stranraer, south-west Scotland, between the Mull of Galloway and Burrow Head (see Figure 7.1 for general location). The beach of Luce Sands and the extensive Torrs Warren sand dunes occupy almost the whole of the head of Luce Bay, extending 11 km from Sandmill on the edge of Sandhead in the west to the coastline east of the Water of Luce. The site covers over 2409 hectares of land and intertidal sandflat (Figures 7.19 and 7.20).

The width of the intertidal beach varies and is greatly dependent on the state of the tide. At mean low-water springs, the beach is on average 750 m wide, but in the east the intertidal flats widen to nearly 2000 m at the exit of the Piltanton Burn. At mean high-water springs, the beach narrows to 0–10 m along much of the foreshore with the drift line skirting the toe of the backing dunes. The beach sediment is well-sorted, fine–medium-grained mineral sand (D_{50} = 0.2 mm) with a very low shell content. A series of well-developed sand-bars with intervening channels are present across the wide, very gently sloping intertidal beach. These bars and channels run along the shore in a generally shore-parallel fashion, although they are not regularly shaped features. Up to six sets of bars, which appeared to be migrating onshore, were noted in February 1993 (Single and Hansom, 1994).

The coastal edge along most of the beach has a low, subdued and accretional form. A gently sloping apron, clad in wheatgrass *Agropyron* and marram *Ammophila*, grades almost continuously from the upper beach and backshore. Although there are clear traces of short episodes of erosion during storms and unusually high tides, accretion has been the dominant process in the recent development of this part of the system, and both the scale and extent of accretion are unusual. However wave-induced toe erosion is evident on either side of the Sandmill Burn embayment in the west of Luce Sands (Figure 7.20) (Single and Hansom, 1994).

The Torrs Warren–Luce Sands dune system is the largest and most complex system of acidic dunes in the south of Scotland. The dune system at first sight appears to be chaotic, with no order to the main direction of the dune crests, blowthroughs, or dune slacks. However, closer examination shows that a general sequence of dune forms begins along the seaward edge where low accretional foredunes exist, especially at the rear of the central and eastern beach (Figure 7.20). These foredunes are arranged in a series of parallel ridges, each individually discontinuous and variable in height, rarely rising above 5–6 m. The younger and more seaward of these dunes are orientated and organized in distinct coast-parallel lines, demonstrating that the winds responsible for their construction blow onshore from the south and south-west (Single and Hansom, 1994). The more landward dunes are securely fixed under marram *Ammophila arenaria* and heather *Calluna vulgaris* (Figure 7.21). Behind much of the length of the seaward dune ridges lie extensive areas of dune slack, which separate the low foredunes from higher dunes to landward. These poorly drained slacks extend over 6 km and are often over 500 m in width. The floors of the slacks are characterized by several low, semi-continuous ridges, composed largely of sand around which freshwater marsh has developed. Since they run sub-parallel to the main beach, they may well represent older, flooded, foredune ridges. Peat is known to exist to unspecified depths in the dune slacks, which now support dense scrub, bushes and thickets.

Towards the east of the beach complex, the damp slack grades into an extensive and well-developed dune area to landward, showing high dune relief and large blowthroughs. The scalloped residual faces of these blowthroughs rise to *c.* 15 m but few of these run shore normal as

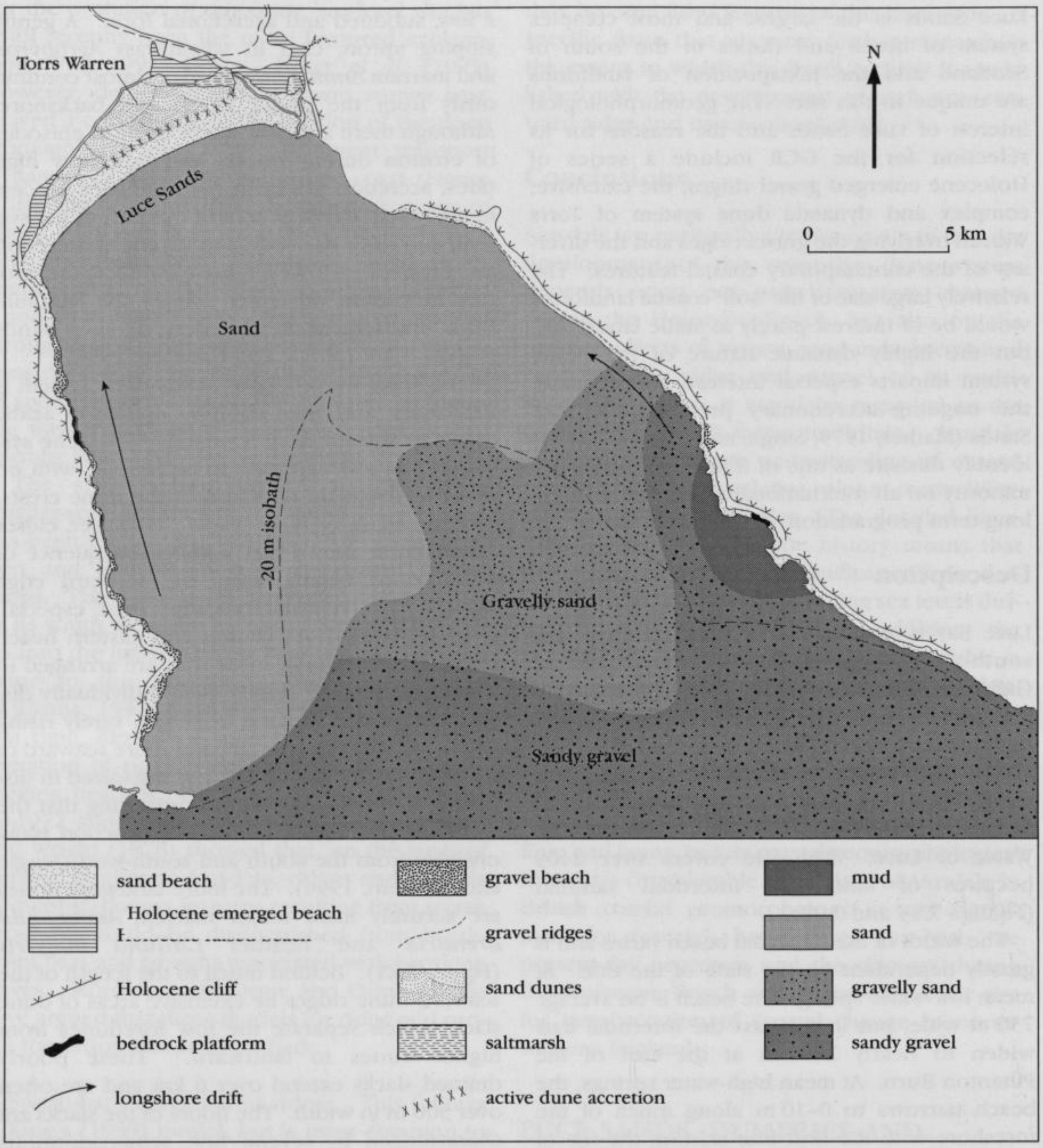

Figure 7.19 Luce Sands is located at the head of a long linear embayment that is floored by extensive areas of sands and gravels. The result of unidirectional wave activity is that sediment is transported northwards on to the beach at Luce Sands. (After Single and Hansom, 1994.)

would be expected if they were controlled by an onshore wind system. The main blowthrough direction is from WNW and relates to winds blowing from this sector. Severe wind erosion has occurred in this area in the past leading to blowthrough excavation down to the water table and the development of substantial erosional slacks. Both dunes and slacks are now largely stabilized, but several areas remain active and active blowthroughs are not uncommon. Nearer the coast, the dunes have a tendency to run beach-parallel and wind-blow activity increases here.

This area of high dunes grades almost imperceptibly landwards into an inner sand plain and old sandhills. This landward part of the dune system consists of a series of rolling sand surfaces interspersed with stabilized sand plains.

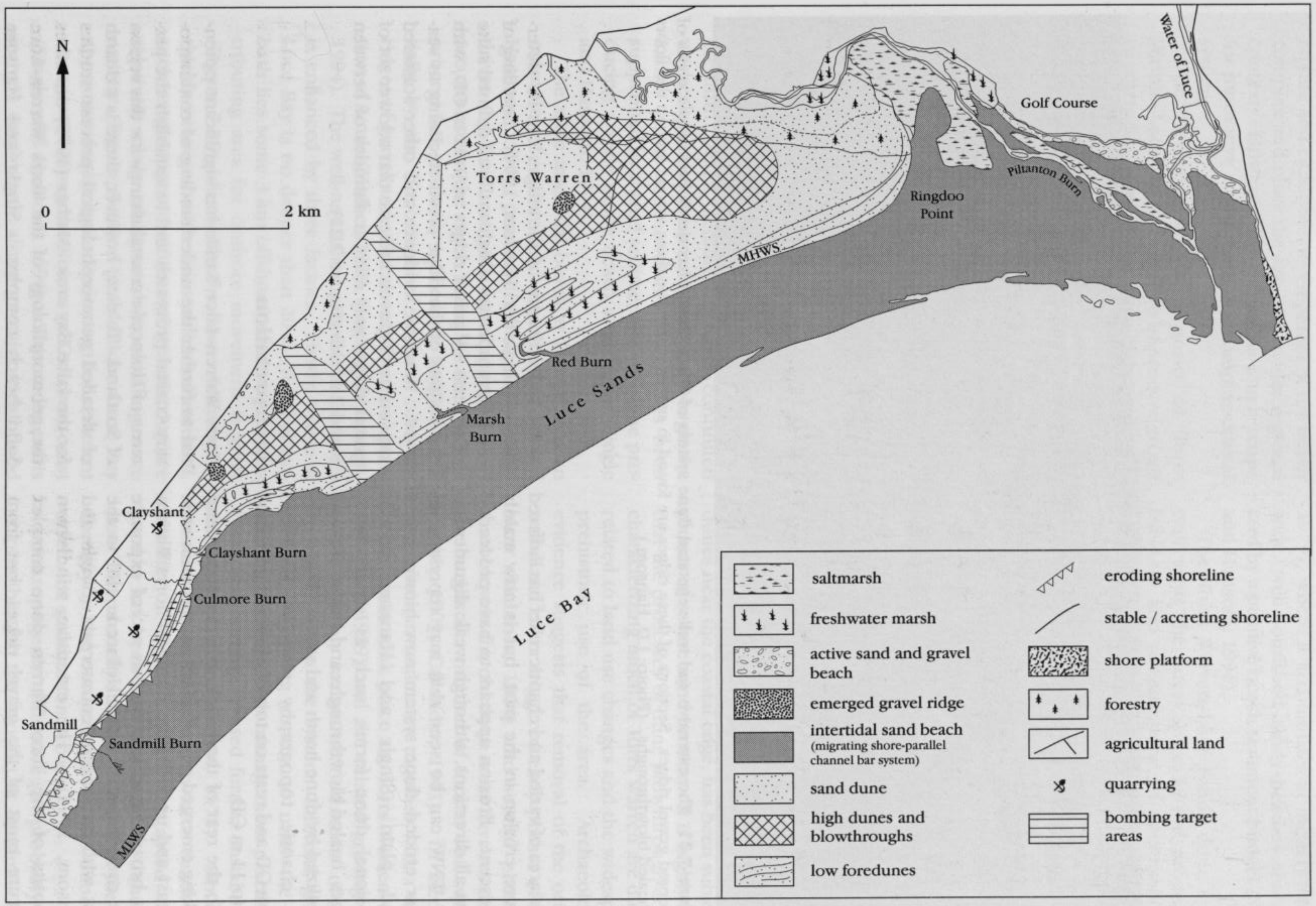

Figure 7.20 The generalized coastal geomorphology of Luce Sands and Torrs Warren showing the wide intertidal area backed by extensive, largely stabilized sand dune. In the central section of the bay, two large areas of dune have been levelled for military use, and access to these areas and to the adjacent intertidal area is restricted. (After Single and Hansom, 1994.)

Figure 7.21 The extensive and well-vegetated dune system of Torrs Warren has developed atop a series of emerged gravel ridges. Sections of these ridges are found in swales within the dune system and on the floors of healed blowthroughs. (Photo: J.D. Hansom.)

This area of varied and chaotic relief has suffered severe erosion in the past, but is now mainly quiescent. Erosion appears to have proceeded from all directions, although weak alignment to the WNW can be seen that may represent an older eroded dune system now blown into a sand plain (Single and Hansom, 1994). Erosional dune forms, such as squat cones, ridges, healed blowthroughs and slacks, are now stabilized by dune heath and scrub. The resultant chaotic topography rises in places to 15 m OD and rests on top of emerged gravels at up to 11 m OD.

To the rear of the beach well-developed and striking emerged gravel ridges extend from west to east and underlie the dunes of Torrs Warren in a broad but discontinuous arc of exposure that connects an eroded Holocene cliff in the west with its eastern counterpart (Single and Hansom, 1994). The extensive windblown deposits of the Torrs Warren dune complex obscure most of the gravel ridges, but from several exposures the general features, orientations and altitudes of the ridges can be determined (Single and Hansom, 1994). Levelling of the ridges indicates a high and well-defined suite of at least 13 gravel ridges at 9–11 m OD, with the heights of the ridge crests declining to seaward. Borehole evidence and other scattered exposures of gravels indicate that a lower set of gravel ridges may exist at altitudes of between 5 and 7 m OD (Figure 7.21).

Interpretation

Torrs Warren–Luce Sands has significant potential to further the understanding of contemporary coastal processes and to establish the patterns of Holocene coastal change for this region of Scotland. To date, however, there is a dearth of detailed geomorphological process studies for the Luce Bay area. Mather (1979) describes the geomorphology of the Torrs Warren–Luce Sand beach complex. Single and Hansom (1994) go further to interpret the process regime and Holocene development of the beach complex and place the site in its wider regional context. However, there remains much scope for innovative research on this complex coastal system.

The Holocene coastal deposits of Torrs Warren–Luce Sands provide an impressive group of emerged features related to a higher sea level. Superimposed on these deposits has developed the largest Scottish dune system south of the River Clyde. Together with a beach complex that is the largest in Scotland, Luce Sands represents an exceptional landform assemblage that records continuous and vigorous coastal deposition during the Holocene Epoch. Plentiful sediment supply has been a characteristic of the Holocene development of Luce Sands. The response of gravel systems to plentiful sediment conditions is generally to add extra ridges onto the seaward face rather than to rework the gravels into even higher ridges (Carter *et al.*, 1987). With a falling sea level, this is manifest at Luce Sands by a multi-ridged strandplain that decreases in altitude to seaward. These conditions of plentiful beach sediments have continued unchecked until the present time, although the earlier gravel sedimentation regime has been supplanted by a sand sedimentation regime producing a wide sandy beach and dunes (Single and Hansom, 1994).

The wide intertidal beach at Luce Bay is an example of a bay-head beach (Single and Hansom, 1994), produced where sediment is driven by unidirectional wave approach and accumulates at the swash limit. In Luce Bay, this process has gradually infilled the bay-head, initially by the deposition of arcuate cross-bay ridges of gravel and subsequently by the deposition of sands (Mather, 1979; Single and Hansom, 1994). The well-nourished nature of Luce Sands is enhanced by three factors. Firstly, much of Luce Bay is no deeper than 20 m (the 9 m isobath lies some 3 km offshore), and so the contributing area for onshore movement is great (Figure 7.19). Secondly, the floor of the bay is thickly veneered with unconsolidated material, such as glaciogenic sands and gravels that are relatively easily transported by shoaling wave activity (Figure 7.19). In addition, Luce Bay appears to function as a major trap for sediment transported along the Rhinns of Galloway coast (Single and Hansom, 1994). This sediment is moved northwards along a major tidal flood channel on the west side of the bay (Mather, 1979), where it accumulates at the bay-head in wide, well-nourished sandy beaches characterized by a positive beach sediment budget (Single and Hansom, 1994).

The Torrs Warren–Luce Sands dune system represents the latest stage in the progressive build-up and redistribution of unconsolidated sediments in Luce Bay. The most landward dunes overlying the emerged gravels are the oldest (Mather, 1979; Single and Hansom, 1994) and their formation immediately post-dates the mid-Holocene sea level fall. Since then, foredune ridges have been added progressively. The chronology of development of these foredunes, and their relationships with the dune slacks and high dune field farther landwards, are as yet imperfectly understood, but it is clear that the development has not been continuous or steady (Mather, 1979). Further research at Luce Sands may help assess the mode of dune development in conditions of plentiful, but pulsed, sediment supply.

Much of the dune system of Torrs Warren, with the exception of the low accreting foredunes near the coastal edge, has been subject to phases of severe wind erosion. It is highly likely that the processes of dune blowthrough activity characterizing much of Torrs Warren are directly related to land use changes and the widespread prehistoric use of the area. Archaeological evidence suggests that removal of the original woodland cover triggered early phases of sand-blow (McInnes, 1964) and several phases of sand-blow in the old dune areas have resulted in the burial of a number of former soil surfaces (Smith, 1903; Callander, 1911). In medieval times, human settlement together with a variety of land-uses took place on Torrs Warren (Jope and Jope, 1959) and the related grazing pressures probably maintained elements of dune instability within the system. Informal grazing and sheep rearing continued until the mid-1930s and dune heath management practises of rotational burning created further instability at this time (Idle and Martin, 1975). Since the present use of Torrs Warren–Luce Sands as a Ministry of Defence (MOD) weapons range, grazing has been curtailed and the dunes are now exceptionally stable over much of the area. Forestry in the northern part of the dunes has aided this stabilization process.

Anthropogenic influence is probably also responsible for the erosion at Sandmill Burn. Here the dunes seaward of the Sandhead caravan park were levelled and a raised flat platform was built out seaward of the coastal edge. Rubble and stacked concrete blocks were used to protect this artificial promontory. The presence of this protected section of coast has led to flank erosion of the adjacent coastline. In an attempt to alleviate erosion, *c.* 1 km of coast has been substantially altered. For example, sand-filled plastic barrels were placed along the eroding dunes in front of both the Sands of Luce and Sandhead caravan parks in 1991 (Single and Hansom, 1994). Not only was this an inappropriate method of coastal protection but it exacerbated erosion to the east as the sand which was used to fill the barrels was dug from a now-eroding remnant dune island (Single and Hansom, 1994).

In common with several other large coastal GCR sites the majority of Luce Bay is owned and managed by the MOD and public access is restricted. With the exception of the two bombing ranges, this land use has conserved much of the site in its natural state, due to access restrictions and the limited recreational use of the beach and dunes. However, small-scale interference along the eroding stretch of coast in the west of Luce Sands may affect the long-term natural evolution of this dynamic system. Any further artificial protection of this coast may result in the reduced transfer of sediment that maintains downdrift accretion.

Conclusions

The principal scientific importance of the Luce Sands GCR site lies in the large and complex system of beach and dunes. The rich variety of contrasting dune morphology includes: low parallel foredunes, dune slacks, high transverse dunes with well-developed blowthroughs, and a complex area of older dunes overlying emerged beach gravels. The dynamic relationships between these components lead to the distinctiveness and importance of the site. The emerged gravel strandplain beneath the dunes, deposited under a higher sea level, adds further interest to the site giving insights to the Holocene development of the complex. Additionally, the ongoing accretionary processes at Luce Sands impart a wider interest as this site is one of few in Britain that displays long-term progradation.

SANDWOOD BAY, SUTHERLAND (NC 220 650)

J.D. Hansom

Introduction

The beach–dune complex of Sandwood Bay, north-western Sutherland (see Figure 7.1 for general location), is among the most dynamic in Britain. The high level of activity of the beach and dune landforms, in a situation where human interference is limited, is of great geomorphological interest. Sandwood Bay is enclosed by cliffed headlands to the north and south and contains a diverse assemblage of spectacular soft coastal landforms. To the landward side of the wide sandy beach, a gravel-cored bar capped with highly dynamic sand dunes impounds the freshwater of Sandwood Loch. Other features of interest include extremely mobile sand dunes with large blowthroughs and climbing dunes that reach altitudes of over 100 m OD on adjacent hilltops (Ritchie and Mather, 1969).

Description

Sandwood Bay GCR site, western Sutherland, encompasses the seaward end of the glacially modified valley of Strath Shinary, and lies seawards of the north-western limit of Sandwood Loch (Figure 7.22). The beach and dune machair complex of Sandwood Bay separates the flooded lower part of this depression (Sandwood Loch) from the sea. The GCR site represents only the western part of the much larger Southern Parphe SSSI. The south-east to north-west orientation of Sandwood Bay corresponds to a structural depression along the junction of the near-vertical cliffs of Torridonian sandstones to the south and the bold convex cliffs cut in Lewisian gneisses to the north (Figure 7.23). The steep sandstone cliffs, which form the south-west limit of the bay, rise to over 90 m and are variously subject to block failure and granular disintegration, giving rise to talus cones in places. As a result, a wide textural range of sediments is contributed to the inshore zone from the crumbling cliffs (Ritchie and Mather, 1969). The gneiss rocks of the north are more massive and resistant and provide little detrital material. Exposures of bedrock crop out in several places within the beach and dune

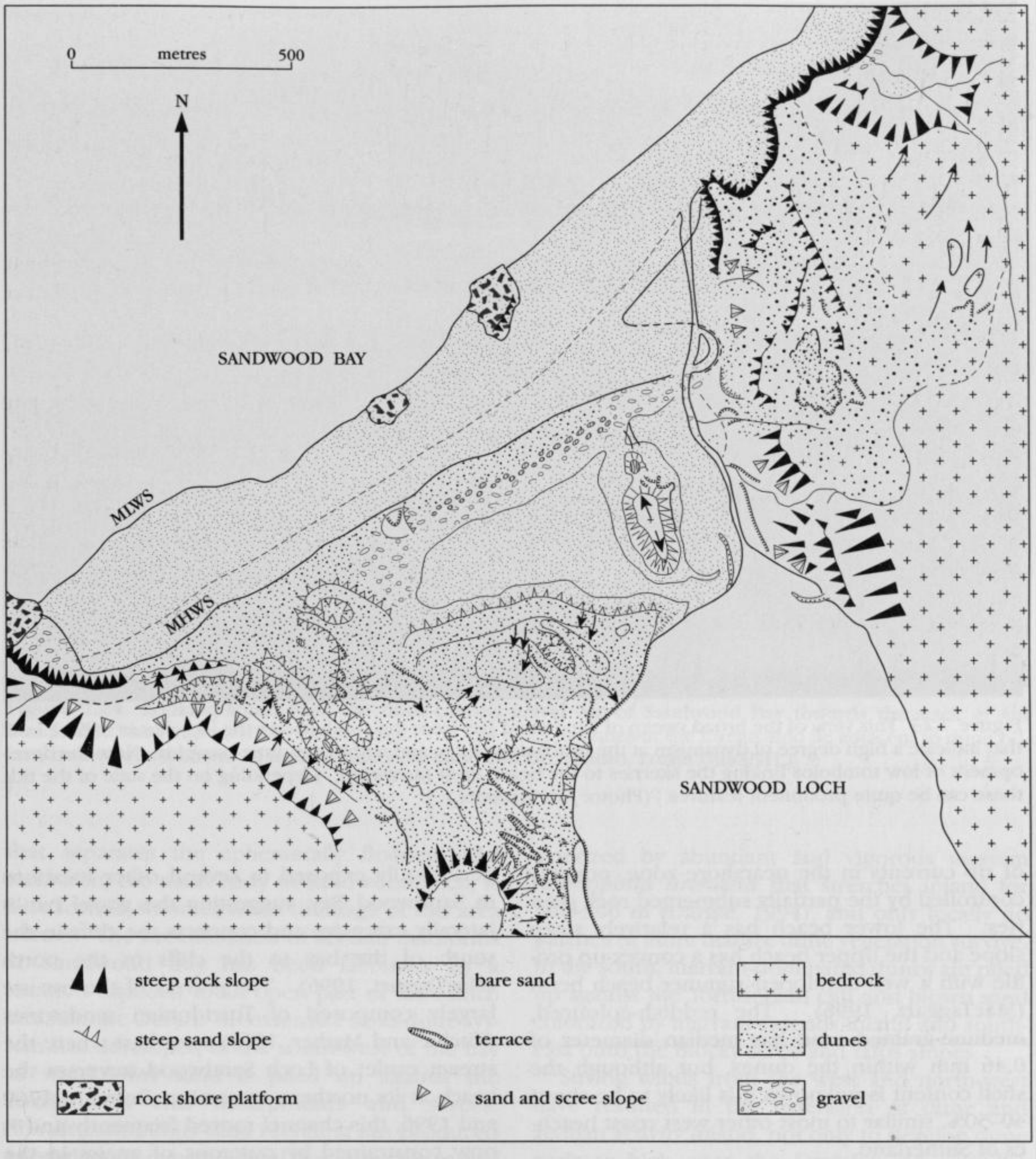

Figure 7.22 Sandwood Bay, Sutherland, is dominated by a large and highly dynamic area of blown sand and machair that lies between the sea and the freshwater Sandwood Loch. Arrows show slope direction. (After Ritchie and Mather, 1969.)

complex (e.g. the low rock skerries at mean low-water springs). In the hinterland the bedrock supports a thin and discontinuous cover of gravelly till. Erosion scars in stream sections within the gneiss reveal the presence of a thin veneer of gritty red till and Torridonian erratics on top of the gneiss testify to ice movement towards the north and north-west.

A wide sandy beach, with an average intertidal width of *c.* 250 m, has developed in this natural structural embayment (Figure 7.23). This exposed Atlantic beach is among the most dynamic in Britain and is characterized by ephemeral bars that develop and erode depending on prevailing wind and wave conditions (MacTaggart, 1996). There is some development

Figure 7.23 This view of the broad sweep of Sandwood Bay from the south shows the large areas of bare sand that indicate a high degree of dynamism at the beach-dune edge and within the dune-complex. Note the development of low tombolos linking the skerries to the beach crest (arrowed). Depending on the state of the tide these can be quite prominent features. (Photo: J.D. Hansom.)

of rip currents in the nearshore zone, possibly controlled by the partially submerged rock skerries. The lower beach has a relatively steep slope and the upper beach has a convex-up profile with a well-developed summer beach berm (MacTaggart, 1996). The reddish-coloured, medium-grained sand has median diameter of 0.46 mm within the dunes, but although the shell content is unknown it is likely to be about 40–50%, similar to most other west coast beaches of Sutherland.

Landwards of the beach a distinctive dune-capped gravel bar impounds the freshwater Sandwood Loch (Figures 7.22 and 7.23). In the centre of the bay, the dunes have an interesting and peculiar form, consisting of a series of upstanding vegetated dune pillars standing on a sand and gravel base. The dune pillars are likely to represent the erosional remnants of a more extensive dune system that previously covered the gravel bar. In July 1996, low embryo dunes were accreting seawards of the dune pillars (MacTaggart, 1996) (Figure 7.24). Gravel is periodically exposed in several other locations in Sandwood Bay, suggesting the gravel bar is laterally extensive and connects the cliffs in the south of the bay to the cliffs in the north (MacTaggart, 1996). The gravels of the bar are largely composed of Torridonian sandstones (Ritchie and Mather, 1969) seen best where the stream outlet of Loch Sandwood traverses the beach at its northern extremity. Between 1969 and 1996, this channel moved frequently and is now constrained by outcrops of gneiss in the north. During the high loch levels of late winter and early spring, several ephemeral streams develop and drain through the dune-capped gravel bar (Ritchie and Mather, 1969; MacTaggart, 1996).

In the lee of the dune-capped gravel bar there is an ephemerally flooded flat surface of bare sand (Figure 7.22). The flooding of this area is mainly due to the freshwater outlet from Sandwood Loch being impounded by the tide, but marine incursions may also flood this area (Ritchie and Mather, 1969). The low sand-bar

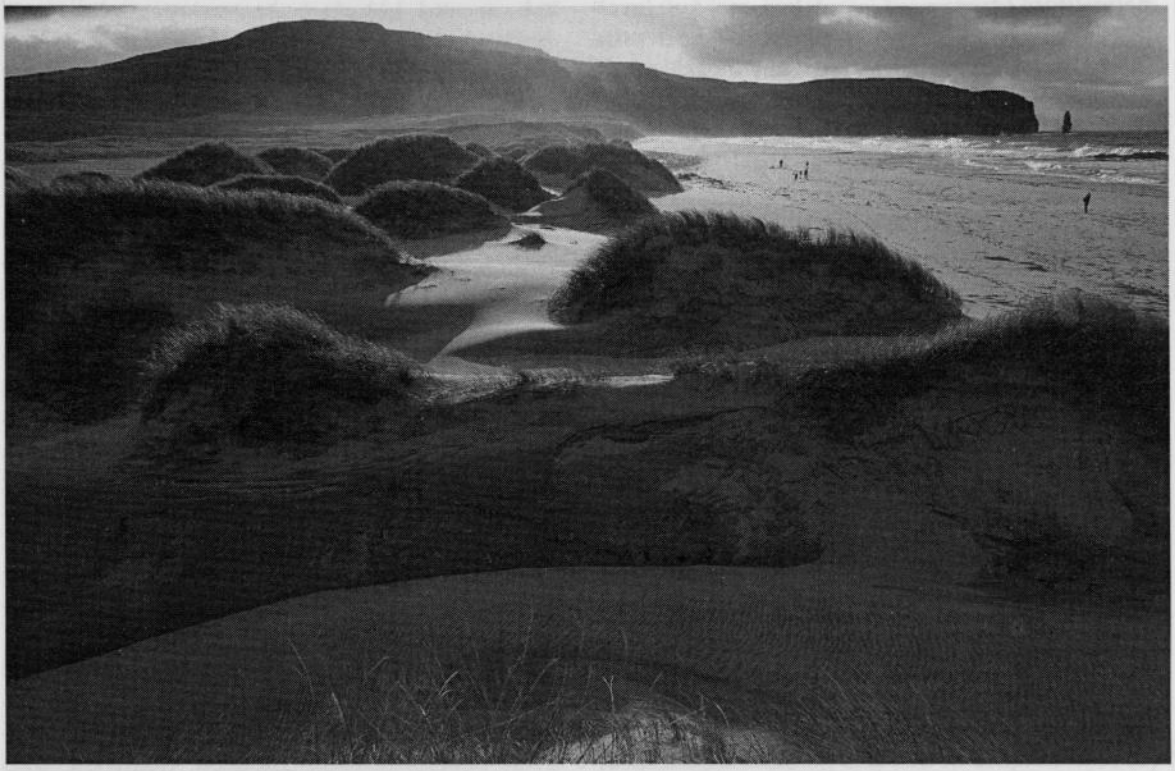

Figure 7.24 Looking south from the dune-capped gravel bar of Sandwood Bay towards the stack of Am Buachaille ('the Herdsman') in the distance. The low embryo dunes in the foreground lie adjacent to dune pillars, he eroded remnants of a more extensive dune cordon. (Photo: Lorne Gill/SNH.)

that separates the ephemerally flooded tidal sand from the main body of Sandwood Loch, is best seen in summer when drainage of this area occurs. The accumulation of aeolian landforms at Sandwood Bay has been favoured by a location exposed to an open part of the Minch and Atlantic Ocean. An extensive sand-dune system has developed in the south-west of the bay as windblown sand is piled up against the Torridonian cliff escarpments and screes. Almost continuous sand recycling has produced exceptionally dynamic sand dunes in this part of the bay and several large elongate blowthroughs trending north-west–south-east are extremely active. Large areas of bare sand characterize this area; in the summer of 1996 there was evidence of considerable sand accretion and sand recycling within the system. The gravel or bedrock deflation bases of the main blowthroughs were covered with drifting sand and large sand aprons extended seawards onto the beach face (MacTaggart, 1996). The immaturity of the dune vegetation gives an indication of the dynamism of the dune system. The main dune area is characterized by abundant and vigorous marram *Ammophila arenaria* that stretches inland for 500–900 m (Dargie, 1994), and only locally do patches of more mature dune vegetation survive. In the south, marram-dominated dunes are piled up against the Torridonian cliff and blown sand colonized by marram extends inland and south-east onto the blocky scree and talus slopes.

Strong winds from the west and north-west have resulted in the extension of dune and aeolian activity inland, not only to develop dune surfaces high onto the Lewisian ridge to the north of the bay, but also to infill the northern part of Sandwood Loch. The lower parts of the northern Lewisian gneiss ridge consist of an assemblage of screes, glacially abraded and smoothed rock surfaces and climbing dunes. An active blowthrough has developed in the climbing dunes. At over 100 m OD, the upper slopes and ridge crest are covered by a well-developed climbing dune that supports a heath-type vegetation. Numerous erosion scars and terracettes characterize the surface as a result of sheep and rabbit grazing and scraping. Subsequent redeposition of exposed sand has created localized accretion and embryonic dune forms within the dissected dune topography (MacTaggart, 1996). On the northern and western shores of the loch the dunes are cliffed and eroded as a result of wave action within the loch (Ritchie and Mather, 1969).

Interpretation

Sandwood Bay is perhaps the best example on the mainland of Britain of a naturally unstable and dynamic beach–dune system. Its relative remoteness has resulted in a system that is now largely unmodified by direct interference by humans and offers the rare opportunity to study natural rates of change in this high-energy and dynamic coastal system. Steers (1973) highlighted the fact that the site requires further investigation; however, perhaps as a result of the relative inaccessibility of the site, no detailed geomorphological work has been carried out to date other than the descriptions by Ritchie and Mather (1969) and MacTaggart (1996). In spite of this it is possible to interpret the landforms of Sandwood Bay in a systematic context.

Sandwood Bay has been glaciated several times in the past, the most recent Devensian ice passing northwards from Torridonian to Lewisian rocks leaving behind a legacy of polished and plucked valley sides and floor, a discontinuous till cover dominated by sandstone material and widespread occurrence of perched sandstone erratics on both the high and low ground (Ritchie and Mather, 1969). The exposures of bedrock on the foreshore and at the base of the dune complex suggest the existence of a discontinuous sill of rock, running transverse to the main structural corridor of Strath Shinary, and forming the foundation of the coastal and aeolian landforms that separate Sandwood Loch from the sea (Ritchie and Mather, 1969).

In common with beaches elsewhere in the Highlands and Islands of Scotland, Sandwood Bay was probably first closed by the development of a gravel barrier beach whose sediments were derived from adjacent rocky coasts and from glaciogenic deposits on the seabed (Ritchie and Mather, 1969). At Sandwood Bay, since the passage of ice was south to north, the local provenance of this glaciogenic material was Torridonian sandstone. The gravel was deposited on and between the various outcrops of bedrock that now underlie the beach and dune system. Since sea-level rise began to slow down in mid-Holocene times, it is likely that the gravel ridges date from this time and were overwhelmed by large amounts of sand that began to arrive from offshore to develop a wide beach and large dune system behind (Hansom and Angus, 2001).

Open to the north-west, and in a wind and wave environment dominated by westerly and north-westerly activity, Sandwood Bay is effectively a sediment trap for both onshore-moving sediments within the bay and for longshore-moving sediment from the cliffs to the south. However, frequent storm wave activity from the north-west is likely to result in a foreshore characterized by periodic reversals in onshore–offshore sediment exchange. Ritchie and Mather (1969) suggest that the Torridonian sandstone has been and remains a continual source of sediment for the coastal landforms of Sandwood Bay. The underlying gravel bar is composed predominantly of Torridonian clasts and the relatively coarse, reddish-coloured, quartzose fractions of the dune sand are derived from the sub-aerially weathered Torridonian cliffs to the south. The process continues today and in July 1996, angular and freshly weathered granules of Torridonian sandstone, blown and fallen from the cliffs behind, covered much of the adjacent beach surface (MacTaggart, 1996). Sand is probably still delivered to Sandwood from offshore, but since shell content is unknown it is difficult to estimate the offshore contribution, other than to suggest that it is now likely to be declining. Other sources of contemporary beach and dune sand come from the cliffs to the south and from sand recycled through the dune system by streams.

The exposed Atlantic location of the bay has also favoured the accumulation of aeolian landforms, and the natural structural embayment to landward has channelled windblown sand inland and uphill to cover the scree and high rock slopes to the north and south of the bay. The highly dynamic nature of the sand dunes and blowthroughs also suggest that there is continual sediment recycling within the system (MacTaggart, 1996). Where the dissection is greatest within the dune system, distinctive upstanding dune pillars (Figure 7.24) are likely to be the result of erosion either by ephemeral streams that drain over the bar during high loch levels or by wave action during storms and extreme high spring tides (MacTaggart, 1996).

Several changes have occurred since Sandwood was mapped by Ritchie and Mather in 1969, particularly in the south. The elongate multiple blowthrough system of 1969 has been modified into three large coalesced blowthroughs that have an amphitheatre-like form. Vertical accretion is widespread and, in 1996, 4–5 m thick aprons of sand had accumulated seawards and to the north of the main faces. Since the main axis of the blowthroughs in 1969 was north-west–south-east, the main direction of advance of the sand removal is assumed to be landwards to feed the dunes behind. However, it is also clear that substantial amounts of sand are also returned to the beach during winds from the south and south-east, and this is also the direction of advance of a high-altitude blowthrough on the northern side of the bay (MacTaggart, 1996).

Conclusions

Sandwood Bay, western Sutherland, contains a spectacular assemblage of soft coastal landforms that have accumulated at the head of Strath Shinary impounding the freshwater Sandwood Loch. The principal geomorphological interest of the site rests in the very high levels of geomorphological activity in the beach and dune landforms, in a situation where human interference is limited, and thus offers a rare opportunity to study natural rates of coastal change. Individual features of interest include the dune-capped gravel bar, highly dynamic and mobile sand dunes, large blowthroughs and climbing dunes that reach hilltop altitudes of over 100 m OD (Ritchie and Mather, 1969). The cliffs that enclose Sandwood Bay are integrally linked to the past and current evolution of the geomorphological system, the sandstone cliffs that are undergoing eosion to the south providing an important sediment source.

TORRISDALE BAY AND INVERNAVER, SUTHERLAND (NC 690 620)

J.D. Hansom

Introduction

The diverse assemblage of beach and dune landforms at Torrisdale Bay, Sutherland, northern Scotland (see Figure 7.1 for general location), is of national geomorphological importance. The dune landforms, which demonstrate various stages of development and dynamism, lie landwards of a wide intertidal sand beach and sit on top of the high, central, glacially scoured rock ridge and the terraces of the River Naver that drains into the east part of the bay and the River Borgie that drains into the west part. Dunes have formed on the hilltop at altitudes of up to 110 m OD on the central rock ridge and are of geomorphological and botanical importance. The site is also of importance from an archaeological perspective because the river terraces contain numerous cairns, hut circles and cist burials that may allow minimum dating of the landform surfaces. Despite the enormous research potential, which is enhanced by ecological and archaeological interests, the site has failed to attract detailed geomorphological research although several descriptive accounts highlight the site's significance (Ritchie and Mather, 1969; Steers, 1973; Bentley, 1996b).

Description

The Torrisdale Bay and Invernaver GCR site (Figure 7.25) encompasses two bays, at the mouths of the rivers Naver and Borgie, which drain into the east and west of the bay respectively. The two rock headlands that enclose Torrisdale Bay (Creag Ruadh on the east and Aird Torrisdale on the west) are formed of highly resistant metamorphic rocks of the Moine series (Ritchie and Mather, 1969). In the centre of the bay, a glacially scoured bedrock ridge is formed of strongly foliated Moine Schists (Ritchie and Mather, 1969). This 110 m OD bedrock ridge is cut by a series of parallel east–west-trending fractures that have been exploited by glacial action to produce a series of depressions or gullies along its flanks. These gullies form important access channels for blown sand to climb to the top of the ridge. The ridge has been extensively glacially scoured in a south–north direction and contains excellent examples of roches moutonnées, with smooth abraded surfaces on the south side (up-glacier) and rough plucked surfaces on the north (down-glacier). Smoothed bedrock surfaces abound and perched blocks, some of which are erratics, are common. Both the River Naver and River Borgie have well-developed glaciofluvial sand and gravel terraces. Ritchie and Mather (1969)

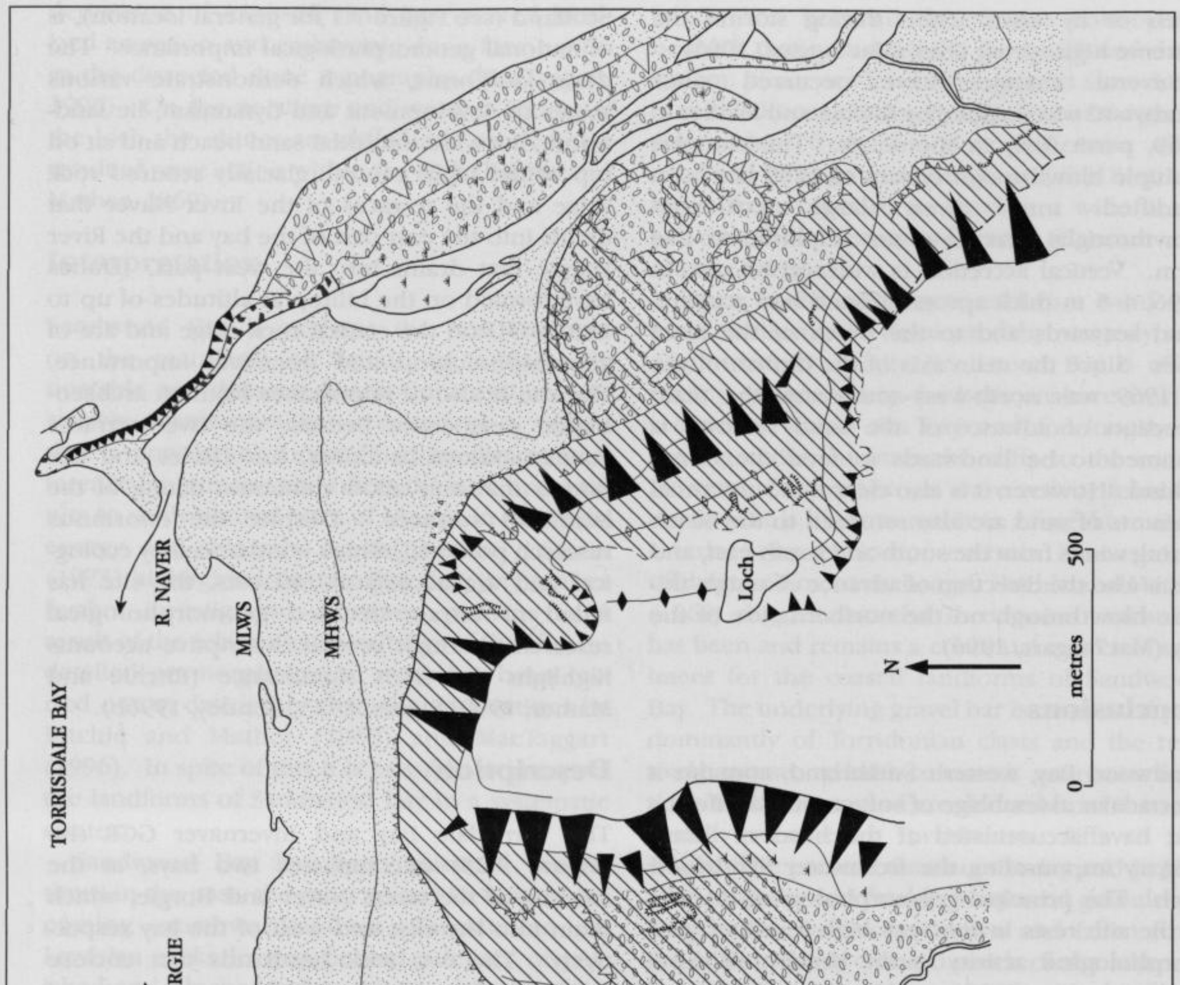

Figure 7.25 The geomorphology of Torrisdale and Invernaver is bisected by a glacially scoured rock ridge that is flanked on either side by glaciofluvial terraces that are capped by windblown sands. The unvegetated upper beach is wide and backed by low dunes. Areas of saltmarsh occur along the exit of the River Borgie. (After Ritchie and Mather, 1969.)

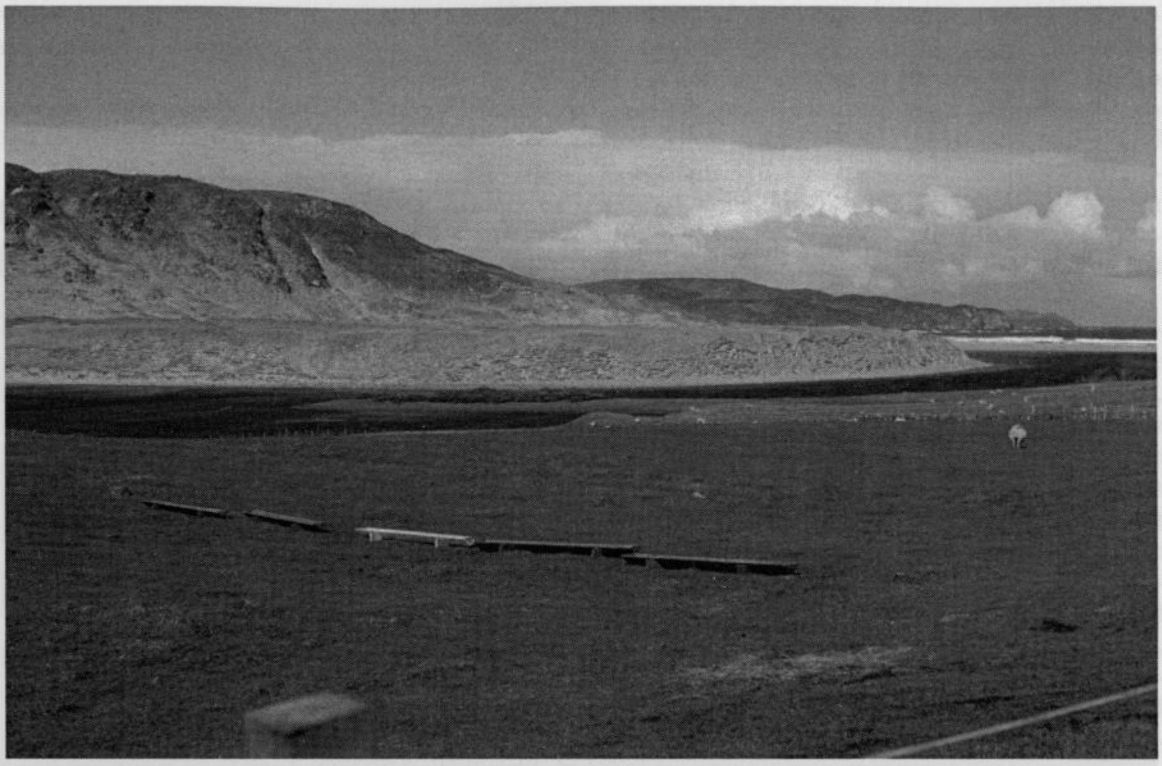

Figure 7.26 The large glaciofluvial terrace at Invernaver viewed from the east is flanked and capped by blown-sand deposits that also climb the ridge behind. The surface of the terrace also supports a wealth of archaeological remains including hut circles and cist burials. (Photo: J.D. Hansom.)

suggest the terraces on the east side of the lower Naver valley correspond to different early sea levels. The most prominent is an extensive flat-topped gravel terrace on the west side of the river at *c.* 15–20 m OD (Figure 7.26). The terrace surface is pitted by a number of kettle holes up to 10 m in diameter (Bentley, 1996b). The south and east sides of the terrace slope steeply down to the valley floor and the steep seaward cliff is fringed with vegetated sand dunes above the wide intertidal beach. A flat-topped gravel terrace at a similar altitude to the extensive Naver terrace forms the eastern side of the Borgie valley.

The wide and flat sandy beach of Torrisdale Bay extends over 1 km in length from the mouth of the River Naver in the east to the mouth of the River Borgie in the west. Extensive areas of intertidal sands characterize both bays and several areas of saltmarsh have developed in the inner reaches (Figure 7.27). At low tide the beach at Torrisdale Bay can be as wide as 950 m, with about 40% of the total beach area lying above high-water mark. The sand has a median diameter of 0.2–0.3 mm and has only 3–4% shell-derived calcium carbonate. Prominent sand-bars extend seawards across the mouths of both rivers. On the bar at the mouth of the River Naver, an area of low (3–4 m high) marram-clad sand dunes has experienced vigorous growth since the 1970s (Bentley, 1996b). Landwards and south of the beach at Torrisdale Bay an extensive dune system has developed, the detailed morphology of which is controlled by the eroded form of the bedrock ridge and the flat-topped glaciofluvial terraces that flank it. The Naver terrace contains a wealth of important archaeological artefacts including cairns, hut circles and cist burials. In contrast, the Borgie terrace has no known archaeological interest and is capped by an extensive (0.5 × 0.5 km) flat dune grassland surface used for grazing.

At the rear of the beach, the coastal edge is characterized by a frontal apron of young vigorous dunes that are mostly relatively stable with vigorous marram *Ammophila arenaria* growth although there is some localized evidence of erosion where the vegetation cover has been stripped. The main dune ridge extends along the back of the beach and drapes the seaward

Figure 7.27 The intertidal saltmarsh and sandflats of the River Borgie exit looking north-west over the low dune area and beach of Torrisdale Bay in the middle distance. (Photo: J.D. Hansom.)

edge of the Naver terrace before curving northwards round the flanks of the central rock ridge to continue into the Borgie estuary. In places the fringing dunes extend southwards onto the Naver terrace surface itself, while farther landwards some low isolated dune features rest on the top of the gravel terrace. An extensive area of dunes has also developed on the west side of Torrisdale Bay, in the triangular-shaped area lying between the Borgie terrace and the central rock ridge (Figure 7.25). The marram-clad dunes of this area are characterized by an irregular and hummocky surface topography and have no preferred alignment. However, the dune slacks occur at a common low altitude and contain standing water or damp surfaces and probably mark the position of the water table (Bentley, 1996b). Gravel is exposed at the base of some slacks (Ritchie and Mather, 1969). This dune system drapes the northern part of the Borgie terrace for up to 50 m southwards before giving way to a much smoother and vegetated dune grassland that extends over the terrace top and thins to the south.

The steep (up to 20°) rock slopes of the central ridge are host to a diverse array of landforms including dunes, bare screes of sand and rock debris and patches of heath. On the northern part of the ridge at the rear of the beach, 9–12 m-high coastal dunes merge into the dunes that are being blown uphill. These climbing dunes are most extensively developed on the north-east and east flank of the ridge, especially where rock depressions permit deeper sand accumulation. For example, the deep gully occupied by the stream flowing east from the loch to the lower River Naver, acts as a funnel for windblown sand. A small dune area has developed near the crest of the ridge at 110 m OD. This unusually high hilltop dune is characterized by numerous erosion scars and terracettes, the result of a combination of wind erosion and sheep scraping. The dune heathland of the ridge are also of considerable ecological interest with unusual associations of mountain avens *Dryas*, heather *Calluna*, crowberry *Empetrum*, sedge *Carex* and juniper *Juniperus* (Ritchie and Mather, 1969) providing a classic example of the 'altitudinal descent' of montane vegetation (Bentley, 1996b).

Interpretation

Ritchie and Mather (1969) describe the Torrisdale Bay area as a 'bewildering melange of landform and landscape elements'. The site comprises a fine assemblage of landforms that relate not only to the Quaternary evolution of the area but also the shorter-term dynamic beach–dune processes. Although no detailed geomorphological research has been carried out, it is possible to interpret the general evolution of this magnificent site from the morphological accounts of Ritchie and Mather (1969) and Bentley (1996b).

The site lies outwith the accepted limits of the Loch Lomond Stadial and so the last ice to override the site is most likely to be of Devensian age, flowing over the central bedrock ridge in a south–north direction and producing scouring, striations, and roches moutonnées (Ritchie and Mather, 1969). During the latter stages of the Devensian glaciation, the valleys of the Naver and Borgie acted as conduits for large volumes of meltwater and sediment discharged from the northern margin of the Scottish ice-sheet. As a result both the Borgie and Naver valleys contain large flat-topped terraces, that are the remnants of larger outwash terraces grading to former sea levels. The lower parts of these terraces were probably trimmed during the higher relative sea-levels of the Lateglacial period and were subsequently isolated as sea levels fell from 15–20 m OD (Ritchie and Mather, 1969). Ritchie and Mather (1969) suggest that fluvial reworking of these outwash terraces provided the sand and gravel for the large intertidal expanse of beach. However, the relative absence of gravel on the beach compared to its great abundance in the terraces may imply that offshore sources of sand were equally important in the initial development of the beach and dunes of Torrisdale Bay. This argument has been rehearsed elsewhere (Hansom, 1999, 2001) but broadly involves onshore delivery of large amounts of glaciogenic sand and gravel, at a time when the sea-level rise slowed during mid-Holocene times. The early arrival of gravel initiated development of gravel ridges that were subsequently inundated by large quantities of sand, which was then distributed into extensive dune and machair systems. However, in contrast to most Scottish beaches and dunes, Torrisdale Bay appears to be relatively stable or accreting. It is likely that the general decline in offshore sediment sources late in the Holocene Epoch has been offset by a ready source of sand recycled from the Naver and Borgie glaciofluvial terraces. The low percentage of shell-derived sand also suggests that onshore rather than offshore sources now comprise the main sand supply to the beaches and dunes.

On the main beach at Torrisdale Bay, a tendency for the beach axis to rotate clockwise over time was observed by Ritchie and Mather (1969), where sand from the east side of the beach on the Naver exit moves west towards the Borgie exit. This may be a function of westerly waves impinging on the east of the beach undergoing less refraction than the waves impinging on the west and so the energy gradient causes longshore transport of sand to the west, an area of lower wave energy. If this is indeed the case, then it may also provide a supply-driven explanation for the striking contrast in the extent and development of windblown depositional landforms on the west and east sides of the bay.

The extensive climbing dunes on the central bedrock ridge probably formed soon after the sandy beach was established, as a result of dune development at the base of the ridge being forced uphill by strong winds from the north, north-west and north-east, assisted by bedrock gullies and depressions that subsequently channelled the windblown sand to altitudes of 110 m OD (Ritchie and Mather, 1969). Dune accretion appears to be continuing today (Bentley, 1996b). The frontal edge of the coastal dunes is relatively stable with low embryo dunes to the seaward side. The wide sand beach and the area of new dunes close to the mouth of the River Naver suggests that sand is still available for dune formation (Bentley, 1996b), in stark contrast to most Scottish beach–dune systems where erosion is the dominant process. The Borgie terrace has a stable dune grassland on its surface, whereas the Naver terrace consists of bare gravel with discontinuous low dune hillocks. This is probably due to the greater exposure to onshore winds at the Naver terrace, but the frequency of cairns, cist burials, grave mounds and other archaeological features may offer another partial explanation in terms of antiquity of anthropogenic influence (Ritchie and Mather, 1969). Nevertheless, similar undiscovered features may lie beneath the dunes of the Borgie terrace.

In summary, the Torrisdale Bay site is of great geomorphological importance on account of the diversity of the landform assemblage and the juxtaposition of glacial, glaciofluvial, and coastal landforms. The combination of dunes that have been blown onshore onto glaciofluvial terraces and, blown to considerable altitude on the central bedrock ridge where dune grasslands have formed, is of considerable interest. These interests are further enhanced by the ecological and archaeological importance of the site. There is considerable scope for further geomorphological research at Torrisdale Bay.

Conclusions

Torrisdale Bay, Sutherland, northern Scotland, contains a diverse assemblage of dune landforms draped over a complex subsurface morphology comprising a glacially scoured bedrock ridge and the glaciofluvial terraces of the River Naver and River Borgie. A wide variety of dune landforms are well developed, demonstrating various stages of evolution and stability. Individual features of particular interest are the dune forms that have developed on the terraces, and the climbing dunes and high-level hilltop dune grassland. It is the juxtaposition of impressive glacial, glaciofluvial, and coastal landforms at Torrisdale Bay that is of outstanding geomorphological significance.

DUNNET BAY, CAITHNESS (ND 215 710–ND 201 682)

J.D. Hansom

Introduction

The wide sand beach of Dunnet Bay, Caithness, (see Figure 7.1 for general location) is backed by a massive, sharp-crested, coastal dune ridge with a gently sloping links plain on its landward side. The general morphology and scale of this extensive beach–dune–links system is unique in Britain. The coastal dune ridge is dissected by numerous spectacular, wide, deep blowthroughs at various stages of development. As blowthrough stability ranges from stable to extremely active, Dunnet Bay provides a key site for studies of blowthrough initiation, growth and natural or artificial stabilization. The dune and links also support important species-rich vegetation and invertebrate communities. Despite the enormous research potential at Dunnet Bay it has failed to attract any detailed geomorphological research, although two mainly descriptive accounts of the site exist (Ritchie and Mather, 1970a; Bentley, 1996c), and Hansom and Rennie (2003) have recently quantified coastal changes.

Description

The GCR site of Dunnet Bay lies at the head of a 4 km-wide, 6 km-long embayment on the north coast of Caithness. Inland, the Dunnet Bay structural depression extends south-eastwards across the country to Sinclair's Bay on the east coast of Caithness. As a result of the enclosed nature of Dunnet Bay, between the high sandstone cliffs of Dunnet Head to the north and the low flagstone platform to the south, it can been described as a sediment trap (Ritchie and Mather, 1970a). In addition, the deep penetration of the embayment means that incoming waves are almost completely refracted, arriving at the beach with their crests parallel to the arcuate beach.

The beach at Dunnet Bay is one of the largest in northern Scotland (Ritchie and Mather, 1970a), extending for over 4 km in a broad symmetrical curve (Figure 7.28). The intertidal zone is wide, with an average width of 180 m, and has a uniformly low gradient of 1–2°. Offshore the seaward gradient is also gentle, at about 1:124 (Ritchie and Mather, 1970a). The beach is composed predominately of relatively fine-grained sand (D_{50} = 0.31 mm) of which 20% is $CaCO_3$ and is flanked by low rocky shore platforms at either end. Immediately adjacent to the rock platforms the upper beach is composed of coarse gravel that then grades to sand.

The wide beach is backed by a massive, steep (>30°) and high dune ridge (Figure 7.29). The backslope of the dune is less steep (12–16°) and has a slightly concave-up profile. The dune ridge reaches a maximum height (up to *c.* 20 m OD) and width (*c.* 350 m) towards the middle of the bay. Both the height and width decline towards the southern and northern ends. Frontal erosion of the dune ridge is evident along almost its entire length (Figure 7.29). In October 1996 the dune face was partially revegetated, and low embryo dunes had formed in places at the back of the beach, a

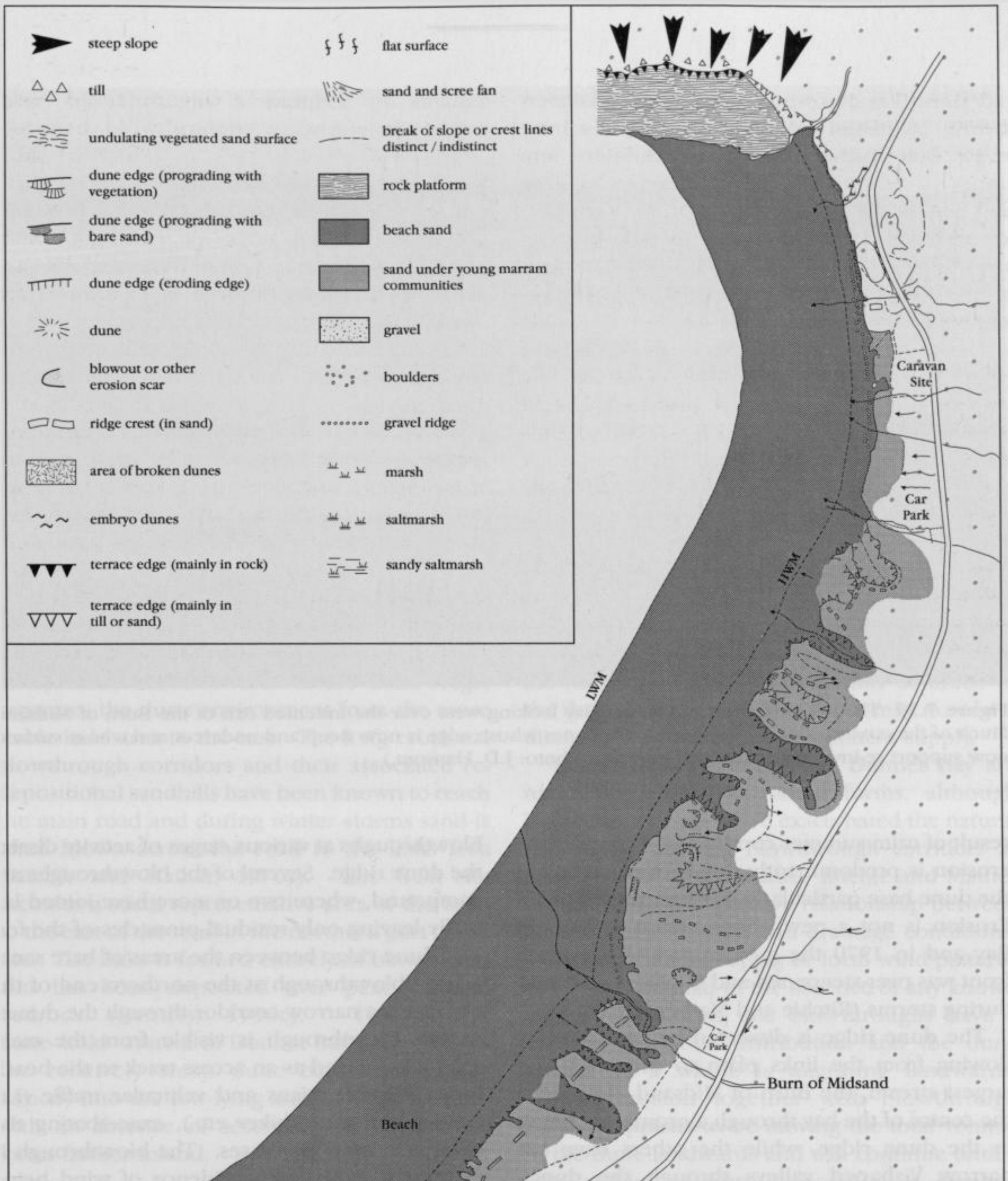

Figure 7.28 The coastal landforms of Dunnet Bay and dunes showing a coastal dune edge that is both undercut by frontal erosion and punctuated in several places by large, linear, blowthrough corridors. (Based on Ritchie and Mather, 1970a and Hansom and Rennie, 2003.)

Figure 7.29 The wide expanse of Dunnet Bay looking west over the indented exit of the Burn of Midsand. Much of the coastal edge comprises mature dunes whose edge is now steep and undercut and whose surfaces now support re-invigorated marram growth. (Photo: J.D. Hansom.)

result of calm summer conditions. Frontal dune erosion is predominantly due to wave attack at the dune base particularly during winter storms. Erosion is not a new phenomenon at Dunnet Bay and in 1970 the greater part of the dune front was over-steepened and in places undercut during storms (Ritchie and Mather, 1970a).

The dune ridge is dissected by nine streams flowing from the links plain to the sea. The largest stream, the Burn of Midsand, flows into the centre of the bay through a prominent break in the dune ridge, while the others have cut narrow V-shaped valleys through the dunes (Bentley, 1996c). Low embryo dunes have developed at the mouth of the Burn of Midsand as a result of the increased local sediment supply.

Morphological diversity of the main dune ridge is created not only by streams but also by numerous spectacular blowthroughs that dissect the dunes. The blowthroughs form several flat-floored, steep-sided erosion 'corridors' through the dune ridge and several saucer-shaped depressions on the windward slope of the wide dune ridge. The blowthroughs, which are often 10–12 m deep, up to 30–40 m wide and often devoid of vegetation, are some of the largest in Scotland (Bentley, 1996c). At least seven large blowthroughs at various stages of activity dissect the dune ridge. Several of the blowthroughs are compound, where two or more have joined laterally leaving only residual pinnacles of the former dune ridge between the areas of bare sand. A large blowthrough at the northern end of the bay forms a narrow corridor through the dunes. As this blowthrough is visible from the main road it is utilized as an access track to the beach for both pedestrians and vehicular traffic (i.e. quad bikes, motorbikes etc.), exacerbating the natural erosion processes. The blowthrough is extremely active, with evidence of wind being channelled through the corridor, scouring the sand and re-depositing it over the ends of the blowthrough as lobes of unconsolidated material. Attempts have been made to stabilize this blowthrough, along with several others, using sand fences and marram planting. This has not been entirely successful; in October 1996 the fences were full of sand and thus were no longer effectively trapping new sediment. The steep slopes flanking the active blowthrough corridors are generally unvegetated and extremely unstable, with evidence of loose sand slumping downslope. Gravel is exposed at the base of several of the larger blowthroughs. Between the large blowthroughs a number of smaller V-shaped blowthroughs penetrate the dune ridge.

Two blowthroughs to the north of the central stream can be described as relict blowthroughs, as although they are stable and fully vegetated they have retained their original form. The stabilization of these blowthroughs was undertaken by the Forestry Commission who used brushwood and the planting of coniferous trees (Ritchie and Mather, 1970a). Although this stabilization has been successful in that the landforms have effectively been frozen *in situ* at a previous stage of high instability, the remaining presence of over-steep slopes and topographical depressions that still channel onshore winds at high velocities may lead to instability at a later date.

Landwards of the wide coastal dune ridge a gently undulating links surface extends for up to 5 km inland. The main Castleton to Dunnet road, which lies landwards of the dune ridge, separates the dune environment from the more stable links area to the east. The long erosional blowthrough corridors and their associated re-depositional sandhills have been known to reach the main road and during winter storms sand is often blown across the road to the links area (Ritchie and Mather, 1970a). The GCR site includes a small representative area of the links to the east of the road in the northern part of the site. The links is formed entirely of blown sand that has been deposited over peat, till and bedrock (Bentley, 1996c). The beach–dune–links system of Dunnet Bay is unusual as the relatively steep dune backslope grades directly into the low-lying area of dune pasture, with an absence of secondary or older dune forms farther inland.

Interpretation

Dunnet Bay forms part of the GCR network of coastal sites on account of its unique dune morphology. The single, massive, sharp-crested coastal dune ridge is dissected by numerous spectacular large blowthroughs at various stages of activity and is backed landwards by an extensive dune pasture and links topography. The scale and range of activity in the various forms of dune blowthroughs and the relatively frequent occurrence of direct wave attack at the base of the dune ridge add geomorphological diversity and enhance the scientific interest. There remains much scope for research at Dunnet Bay particularly concerning the initiation, growth and stabilization of both wind- and wave-induced erosional forms.

Steers (1973) describes Dunnet Bay as 'a feature of primary importance in the coast of Scotland' on account of its enclosed nature between the high sandstone cliffs of Dunnet Head to the north and the low flagstone platform to the south. Since it is so enclosed it acts as an effective sediment trap: the only escape for sand from the bay is landwards (Steers, 1973). It is thus not surprising that a wide, high dune system and extensive links plain has accumulated landwards of the enclosed bay (Ritchie and Mather, 1970a; Steers, 1973). It has been suggested that the gentle offshore gradient (1: 124) of the sand-covered seabed implies there is a continuing reserve of sediment in Dunnet Bay (Ritchie and Mather, 1970a). However, the presence of the large active blowthroughs and frontal erosion of much of the dune face suggests that there may now be a diminution in the offshore sediment supply.

The large blowthroughs at Dunnet Bay are naturally induced erosional forms, although human activity may have exacerbated the natural process by utilizing blowthrough corridors as access tracks to the beach. Ritchie and Mather (1970a) found no positive relationship between blowthrough location and drainage conditions, offshore sediment supply or local wind patterns and conclude that, in the absence of any known trigger mechanism, the blowthroughs have a random stochastic distribution and the dune barrier as a whole is migrating landwards. Frontal erosion together with blowthrough advance appears to be moving the total volume of the dune landwards and will continue until a new stable equilibrium position is reached (Ritchie and Mather, 1970a). This erosion may be due to an increase in wave and wind energy from the north-west or a decrease in the offshore sediment supply (Ritchie and Mather, 1970a). As with the majority of coastal dune systems in Scotland, the dominant process at Dunnet Bay appears to be one of erosion and coastal retreat, although recent artificial stabilization methods have affected the natural evolution of this system. Stabilization of the blowthroughs by planting has been relatively successful: two of the larger blowthroughs are no longer active. The use of sand fencing in several of the larger active blowthroughs, although not entirely effective and in need of maintenance, has limited landward sand transfer. Hansom and Rennie (2003) have recently quantified the rate of retreat of the coastal edge at Dunnet Bay: between 1968 and 1998, 3.6×10^5 m^2 was lost at rates of 20 m a^{-1} mainly in the centre and north of the beach.

The relatively steep dune backslope of the main dune ridge and the absence of secondary ridges or extensive dune forms inland has been attributed to the frequency of strong winds from the south-east channelled by the structural depression between Sinclair's Bay and Dunnet Bay (Ritchie and Mather, 1970a). The to-and-fro nature of winds through this structural corridor may account for the vigour and rate of development of the blowthrough erosion corridors, which once initiated may be attacked by winds from both directions. Strong onshore storm winds from the north-west appear to be more dominant. Further research on the initiation, growth and development of these blowthroughs is required.

Gravel is exposed at the base of several blowthroughs. It has been suggested that the dune system at Dunnet Bay may rest on a gravel basement of emerged ridges and bars (Ritchie and Mather, 1970a; Steers, 1973) as is the case in many Scottish coastal dune systems (e.g. Culbin, Luce Sands and Strathbeg, see GCR site reports). This remains to be fully investigated and as no detailed height measurements are available it is unknown if these gravel forms are related to the present or to a former higher sea level. More research is warranted.

Conclusions

The unique general morphology of Dunnet Bay, which consists of a single, massive, sharp-crested dune ridge leading inland to a gently-sloping extensive links plain, is of immense geomorphological importance. The 4 km-wide arcuate sand beach is backed by a massive, steep (>30°) sharp-crested dune ridge reaching a maximum height of *c.* 20 m OD and width of *c.* 350 m. The low links plain extends up to 5 km landwards of the dune ridge. The morphology of this massive ridge is extremely diverse. It is cut by several small streams draining into the bay and, perhaps more significantly, at least seven large blowthroughs dissect the ridge. The blowthroughs, which are often 10–12 m deep and up to 30–40 m wide, are some of the largest in Scotland (Bentley, 1996c) and are at various stages of activity, ranging from stable to extremely active. The effects of artificial stabilization of the landforms is evident – at least two large blowthroughs are now essentially relict landforms stabilized by dune planting, while others have been partially stabilized by the use of sand fencing. The scale, dynamism, range of activity and diversity of the blowthroughs in this massive coastal dune ridge is of great geomorphological interest.

BALTA ISLAND, SHETLAND (HP 660 075)

J.D. Hansom

Introduction

The small uninhabited island of Balta is 5 km long and lies in a north–south orientation at the mouth of the Balta Sound, off the west coast of Unst, the northernmost island of the Shetland archipelago (see Figure 7.1 for general location and Figure 7.30). The island contains a continuous veneer of vegetated sand extending across Balta Island from a north-west facing bay at South Links through two low cols almost to the 45 m-high eastern sea-cliffs. The sand beach grades into a gravel storm ridge on the upper beach, with the coastal edge being marked by an erosional dune scarp. An extensive dune grassland plain lies behind and, although frontal dunes are absent, it is the most complete dune grassland system in Shetland (Mather and Smith, 1974; NCC, 1976). However, the complex is in an advanced stage of dissection due to a combination of rill dissection and severe wind deflation, probably due to overgrazing by the large rabbit population. In places the dune grassland has been deflated down to a base-level of aeolian calcarenite (Mather and Smith, 1974). This, together with the high rates of deflation, make this site important as a dynamic example of a beach–dune grassland–cliff continuum (MacTaggart, 1999).

Description

The morphology of Balta Island is markedly asymmetrical with the east coast characterized by 45 m-high cliffs, deeply indented with geos, contrasting with the low, more sheltered west-facing coast. The island is composed mainly of

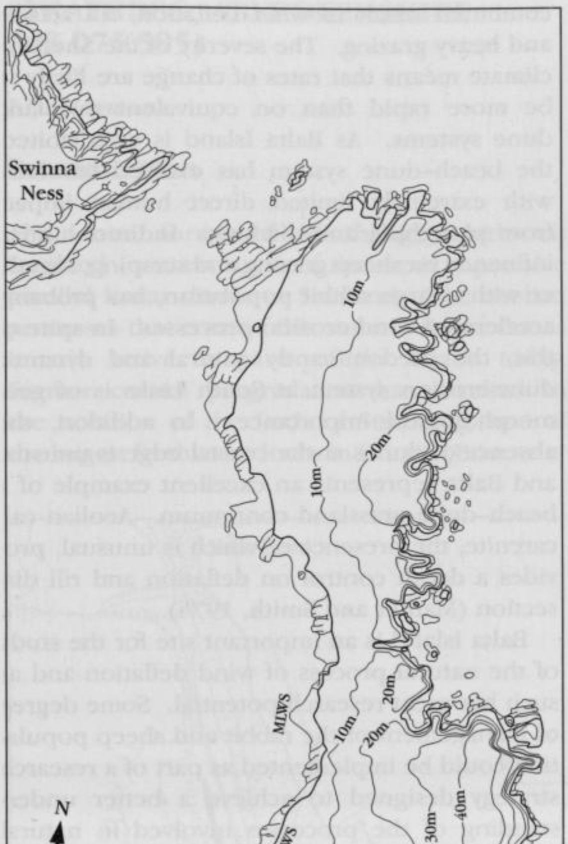

Figure 7.30 Balta Island, Unst, Shetland, is low in the west and high in the east. It is mainly rocky except where sand is blown up-slope from the beach at South Links. (After MacTaggart, 1999.)

metagabbros (NCC, 1976) and the terrain generally consists of ice-scoured bedrock with a patchy till cover and many perched blocks. The only beach on Balta is a 200 m arc of sand at South Links on the west coast. This is backed by extensive windblown sand deposits of variable thickness that sweep across the island via two cols almost to the eastern sea cliffs. It is this extensive beach–dune grassland–cliff continuum that forms the GCR site of Balta Island (Figure 7.31).

Two intertidal rock platforms form the northern and southern limits of the beach at South Links. Fine-grained shell-sand dominates the lower beach and a gravel storm ridge, partly concealed by an apron of blown sand, forms the upper beach. Dunes are absent and the coastal edge backing the beach consists of eroded dune remnants separated by bare sand areas. These remnants, although indicative of severe erosion

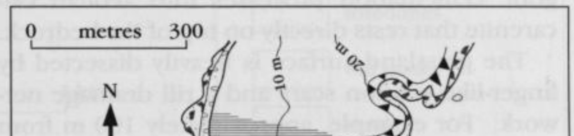

Figure 7.31 The geomorphology of Balta, Unst. There are no dunes but instead the site supports a wide expanse of climbing dune grassland some of which has been eroded into low escarpments. In places the dune surface has been eroded down to a base level of calcarenite by both wind deflation and rill erosion. (After MacTaggart, 1999.)

in the past, appear to be relatively stable and well-vegetated (Mather and Smith, 1974). The underlying gravel storm ridge affords partial protection to the dune grassland toe during storm wave action but the presence of erosional remnants suggests that this may not always be so.

Landwards, some 8 ha of dune grassland veneers a large shallow amphitheatre in the ice-scoured bedrock. Several bedrock knolls carrying perched blocks protrude through the plain from the irregular bedrock surface beneath and this is also reflected in the varying gradient and thickness of the blown sand deposits. The sand thickness decreases rapidly eastwards from depths of over 2 m on the lower parts of the system, thinning to 0.5 m towards the cols on the eastern side (Mather and Smith 1974). These slopes of climbing dune grassland are often in excess of 30° (Mather and Smith, 1974). In places, where the lower levels of the dune sands are close to the water table, they have undergone cementation processes into aeolian calcarenite that rests directly on top of the bedrock.

The grassland surface is heavily dissected by finger-like erosion scars and a rill drainage network. For example, approximately 100 m from the coastal edge, a 1–1.5 m-high active erosion scarp gradually extends inland along a crenulated front. The scarp is characterized by numerous erosion scars whose distal extension inundates the adjacent turf with re-deposited blown sand. The erosion of the surface is also initiated by the numerous small rills that form a radial pattern converging on the lower centre of the South Links amphitheatre. These small rills are ephemeral features, and appear as overland flow becomes concentrated on the lower surfaces after heavy rain. Higher up, subsurface drainage is facilitated by the numerous rabbit burrows that pit the dune surface. Inland of the crenulated erosion scarp, erosion scars and deflation are less common and tend to be localized on the floors of depressions where subsurface drainage is concentrated (Mather and Smith, 1974). It is likely that heavy rabbit and sheep grazing and scraping has exacerbated the processes of wind erosion at South Links.

Interpretation

Balta Island contains the most complete dune grassland system in the Shetland Isles (Mather and Smith, 1974; NCC, 1976). The complex is at an advanced stage of natural dissection, as a combined result of wind deflation, rill activity and heavy grazing. The severity of the Shetland climate means that rates of change are likely to be more rapid than on equivalent mainland dune systems. As Balta Island is uninhabited, the beach–dune system has evolved naturally, with extremely limited direct human impact from ploughing and ditching. Indirect human influence via sheep grazing and scraping, together with a large rabbit population, has probably accelerated wind erosion processes. In spite of this, the predominantly natural and dynamic dune-erosion system at South Links is of geomorphological importance. In addition, the absence of dunes at the coastal edge is unusual and Balta represents an excellent example of a beach–dune grassland continuum. Aeolian calcarenite, the presence of which is unusual, provides a depth control on deflation and rill dissection (Mather and Smith, 1974).

Balta Island is an important site for the study of the natural process of wind deflation and as such has great research potential. Some degree of management of the rabbit and sheep population could be implemented as part of a research strategy designed to achieve a better understanding of the processes involved in natural deflation. However, as yet Balta has failed to attract any detailed scientific research, although the outstanding geomorphological importance of the site has been recognized (Mather and Smith, 1974; NCC, 1976).

Conclusions

A continuous dune grassland veneer extends across the small uninhabited island of Balta from the north-west-facing sand beach through two low cols to the 45 m-high eastern sea cliffs. A combination of rill dissection, severe wind deflation and a high rabbit population has resulted in dissection of the dune surface. A crenulate erosional scarp with linear 'finger' erosion scars is gradually extending landwards into the dune grassland. In places the surface has been deflated to a base level where an unusual outcrop of aeolian calcarenite occurs (Mather and Smith, 1974). The high rates of natural deflation and dissection at a site where there has been limited human interference is of geomorphological importance and Balta Island provides an excellent research area to study the end results of such erosion.

STRATHBEG, ABERDEENSHIRE (NK 075 595)

J.D. Hansom

Introduction

The dune forms of Strathbeg, north-east Scotland (contain some of the most impressive parallel linear dunes in Scotland. The aeolian processes that created this suite of linear dunes remain active in parts of the beach today. Former coastal progradation has resulted in the isolation of the Loch of Strathbeg, one of the largest freshwater lochs in Britain (Bourne *et al*., 1973), which now lies *c*. 1 km inland and is separated from the open coast by the spectacular dune field. The landward dunes lie on top of a series of Holocene emerged gravel beaches, the initial deposition of which resulted in the enclosure of an inlet now occupied by the Loch of Strathbeg (Walton, 1956; Ritchie *et al*., 1978). In addition, Strathbeg contains spectacular examples of wind erosional processes in large-scale coastal dune ridges. Large blowthroughs and deflation plains have been excavated naturally down to the underlying gravel ridges in the southern part of the dune system.

Although the general evolution of Strathbeg has been described (Walton, 1956; Ritchie *et al*.,

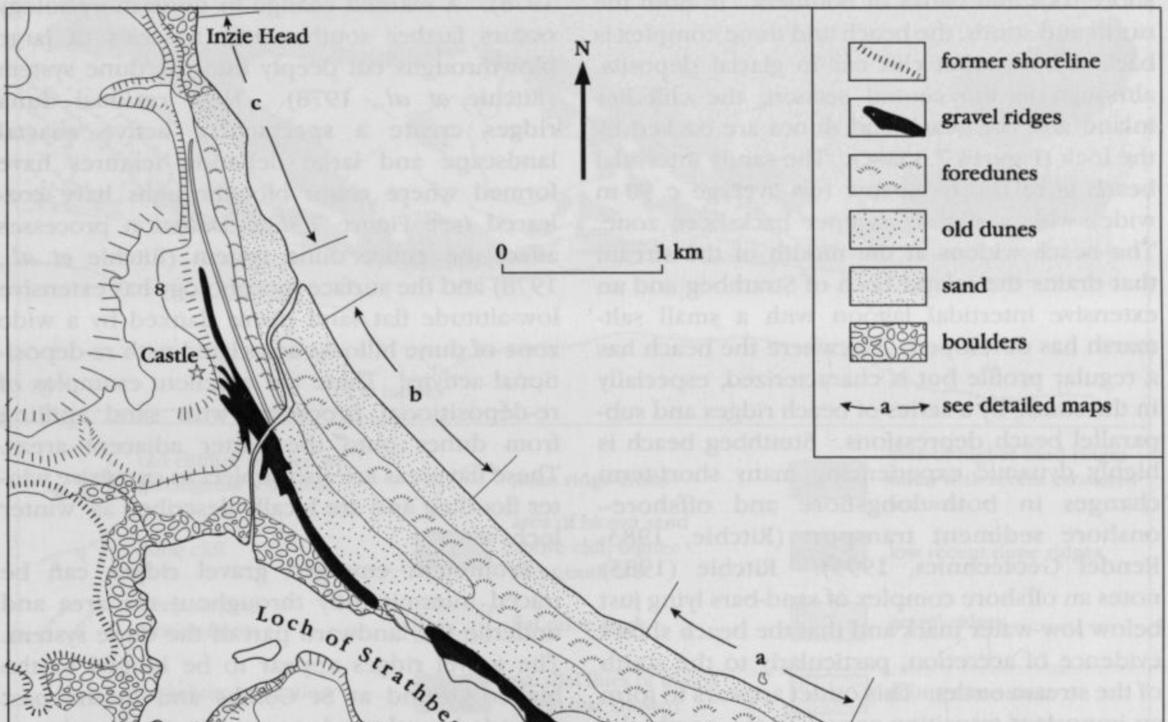

Figure 7.32 Generalized coastal features of Strathbeg, showing enclosure of the Loch by gravel ridges and a series of old dune ridges fronted by lower foredunes. Heights are in metres OD. The detailed sections a–c are shown in Figure 7.33a–c. (After Walton, 1956.)

1978; Ritchie, 1983), no detailed recent research has been undertaken concerning either the processes operating or the chronology of its geomorphological evolution.

Description

The GCR site of Strathbeg covers a total coastal length of *c.* 7.1 km between Rattray Head in the south and Inzie Head in the north, this north-eastern facing coastline marking the transition between the open North Sea and Moray Firth coasts (see Figure 7.1 for general location and 7.32 for detailed geomorphology). In the north the beach is fronted by a low intertidal rock platform and in the south, at Rattray Head, by offshore rock and banks of boulders. In both the north and south, the beach and dune complex is backed by a relict cliff cut in glacial deposits, although in the central section, the cliff lies inland and the beach and dunes are backed by the loch (Figures 7.33a–c). The sandy intertidal beach is relatively narrow (on average *c.* 90 m wide) with a slightly steeper backshore zone. The beach widens at the mouth of the stream that drains the inland Loch of Strathbeg and an extensive intertidal lagoon with a small saltmarsh has developed. Elsewhere the beach has a regular profile but is characterized, especially in the south, by a series of beach ridges and subparallel beach depressions. Strathbeg beach is highly dynamic experiencing many short-term changes in both longshore and offshore–onshore sediment transport (Ritchie, 1983; Rendel Geotechnics, 1995). Ritchie (1983) notes an offshore complex of sand-bars lying just below low-water mark and that the beach shows evidence of accretion, particularly to the south of the stream outlet. This outlet appears to form an important transition zone. To the north, the coastal edge consists of a steep sand-cliff (4–7 m high) which is undergoing active erosion (Ritchie, 1983). For several hundred metres on either side of the tidal sand-floored lagoon and meandering stream channels of the outlet, the coastline is prograding with fine examples of embryo and young foredune ridges, probably as a result of local sand feed from the lagoon. South of the outlet there is a large asymmetric dune ridge rising to over 8 m OD (Ritchie, 1983), which encloses the long narrow tidal lagoon and small, sandy saltmarsh associated with the loch outlet (Figure 7.33b). There is evidence of active sand accumulation on the dune crest and slopes (Ritchie, 1983).

Landwards of the beach there is an extensive and complex series of dune ridges backed by low dune grassland. At least seven parallel linear dune ridges, with a relatively regular summit altitude of 6–9 m above beach level and separated by shallow depressions occur in the north and central part of Strathbeg (Figure 7.33a). This general pattern of parallel dune ridges is broken in places by irregular dune topography as represented by areas of hillocky and transverse dune ridges. The dune morphology close to the loch outlet is particularly complex and 18 separate dune crests occur between the outer beach and the loch margin some 1.2 km inland (Figure 7.33b) (Ritchie *et al.*, 1978). A marked change in dune morphology occurs farther south where a series of large blowthroughs cut deeply into the dune system (Ritchie *et al.*, 1978). High residual dune ridges create a spectacular, active coastal landscape and large deflation features have formed where major blowthroughs have coalesced (see Figure 7.36). Deflation processes affect the entire dune system (Ritchie *et al.*, 1978) and the surface morphology has extensive low-altitude flat sand plains flanked by a wide zone of dune hillocks associated with re-depositional activity. There are excellent examples of re-depositional processes with sand spilling from dunes onto the flatter adjacent areas. These flat areas are also subject to extensive winter flooding and are locally described as 'winter lochs'.

Prominent emerged gravel ridges can be traced intermittently throughout the area and underlie the landward part of the dune system. The gravel ridges appear to be hinged to the higher ground at St Combs and in the past extended southwards to progressively enclose a former inlet whose position is now occupied by the Loch of Strathbeg (Walton, 1956; Ritchie *et al.*, 1978). At the northern end, a number of parallel gravel ridges terminate, sometimes with recurved ends, a short distance to the south-east of the present outlet of the loch. South of this point the gravel bars coalesce to form one main ridge. Farther south the gravel forms the south-east margin of the loch and recurves at the southern distal end terminate in the loch itself (Walton, 1956).

The freshwater Loch of Strathbeg is shallow (1–2 m deep) approximately 3 km long and 1 km wide (Bourne *et al.*, 1973). The loch is

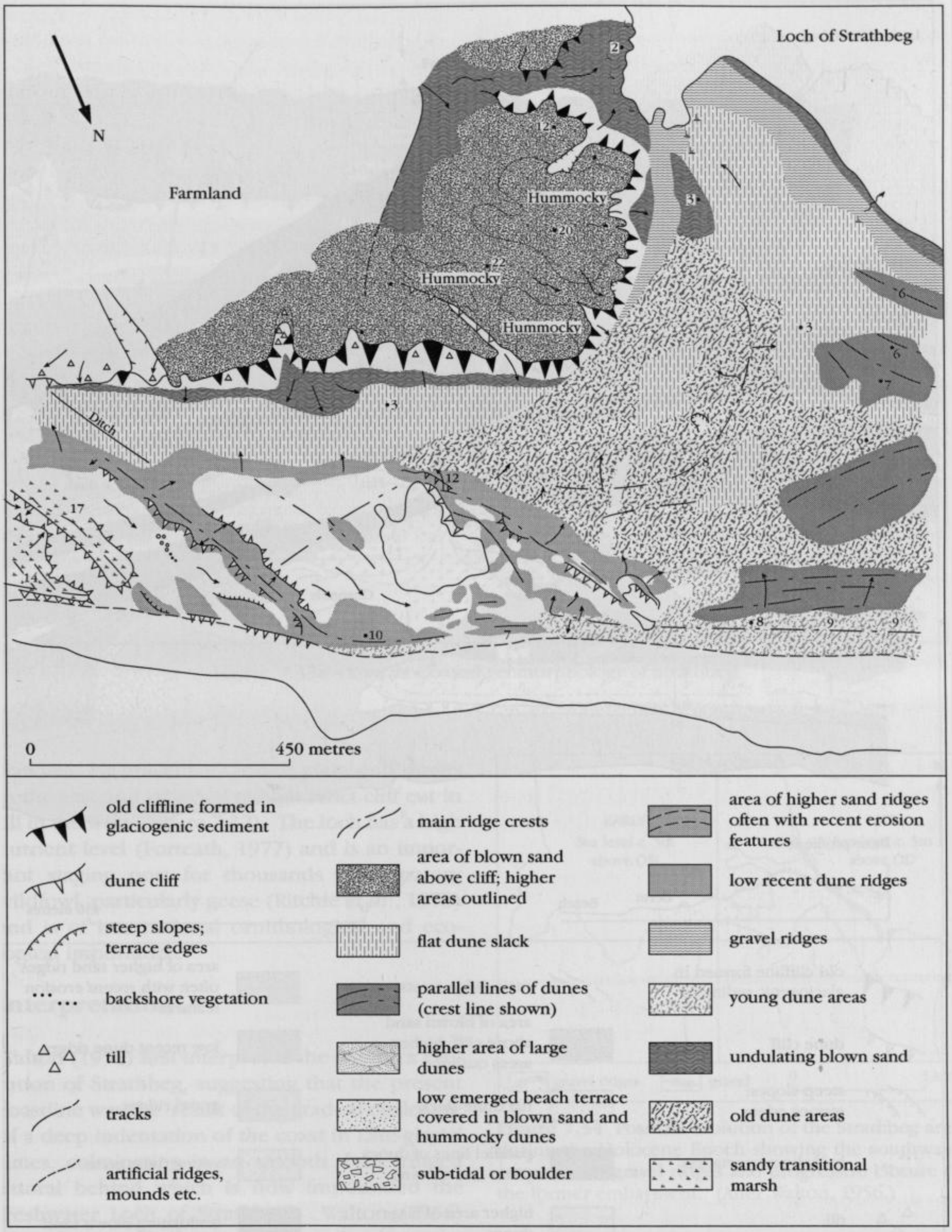

Figure 7.33a–c Detailed coastal geomorphology of the (a) south, (b) central and (c) north sections of Strathbeg, showing the extensive series of shore-parallel dune ridges punctuated by the outlet from the loch. Representative sections through ×–× are also shown. Arrows indicate direction of slope. The figure is continued overleaf. (After Ritchie *et al.*, 1978.)

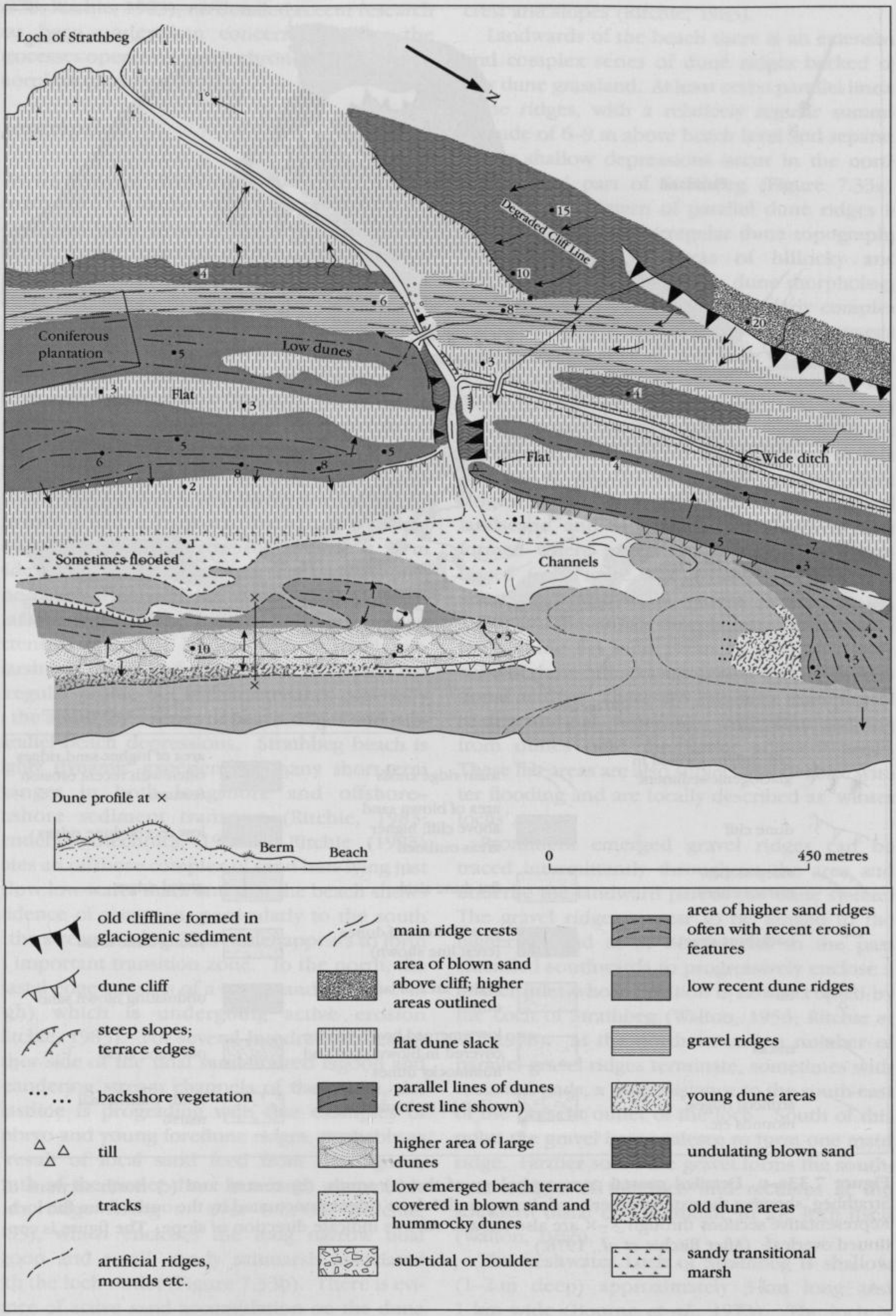

Figure 7.33b – *contd.* Coastal geomorphology of Strathbeg.

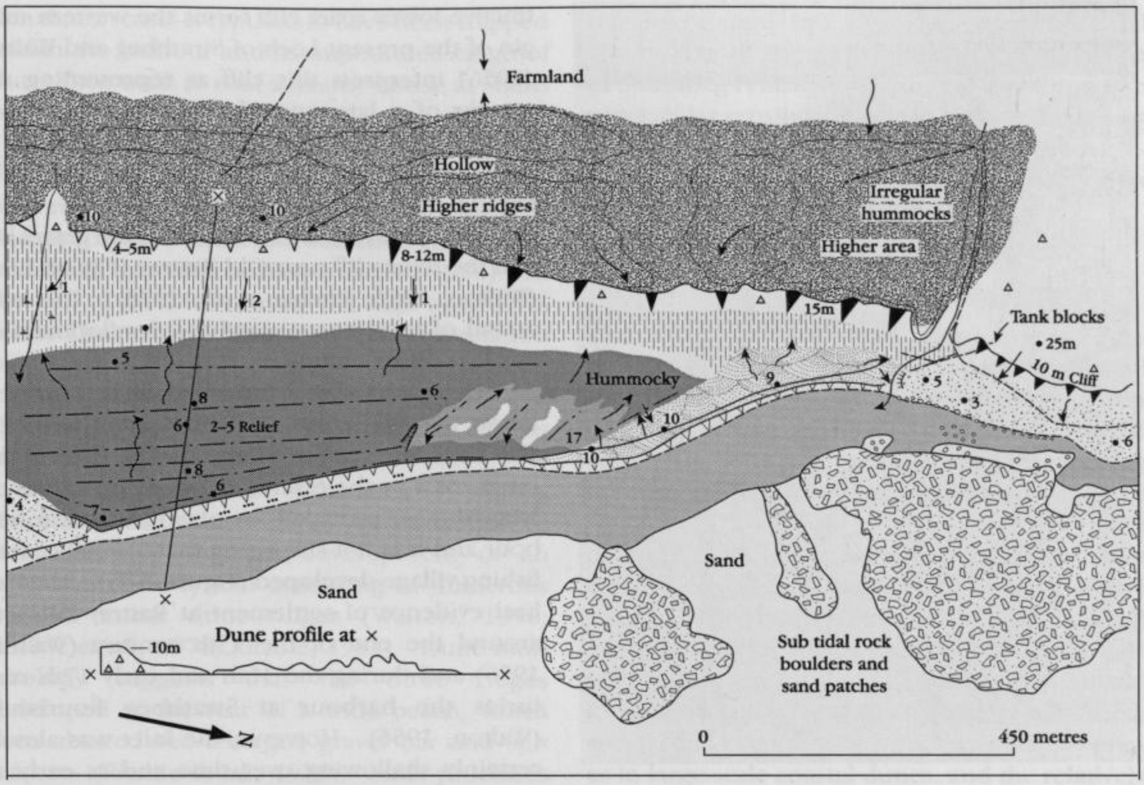

Figure 7.33c – *contd.* Coastal geomorphology of Strathbeg.

bounded by gravel bars, dune plain and dunes in the east and by a 5–9 m-high relict cliff cut in till in the west (Figure 7.32). The loch has a high nutrient level (Forteath, 1977) and is an important staging post for thousands of migratory wildfowl, particularly geese (Ritchie *et al.*, 1978) and is of international ornithological and ecological importance.

Interpretation

Walton (1956) first interpreted the complex evolution of Strathbeg, suggesting that the present coastline was the 'result of the gradual enclosure of a deep indentation of the coast in Late-glacial times, culminating in an smooth dune-fringed littoral behind which is now impounded the freshwater Loch of Strathbeg'. Walton (1956) identified two higher relative sea levels in the area by using remnants of degraded relict cliffs cut in till and now draped in vegetated blown sand deposits. Higher sea levels following deglaciation resulted in inundation possibly to a height of *c.* 16 m OD (Walton, 1956) and at this time (15 000–14 000 years BP), the Strathbeg area was a large inlet, possibily with several offshore islands (Figure 7.34). Relative sea level then fell to below present before rising again sometime possibly around 7000 years BP. A dis-

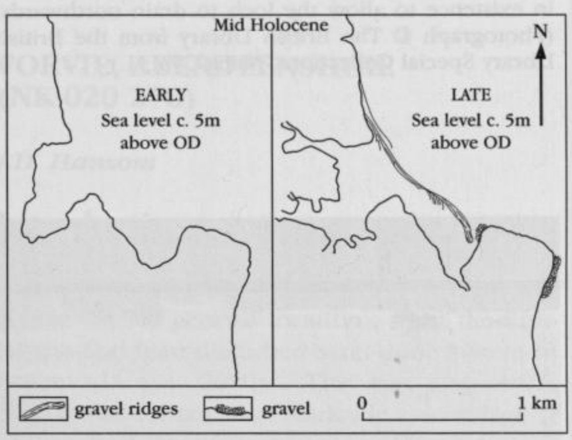

Figure 7.34 Possible evolution of the Strathbeg area during the Holocene Epoch showing the southward extension of gravel ridges and progressive closure of the former embayment. (After Walton, 1956.)

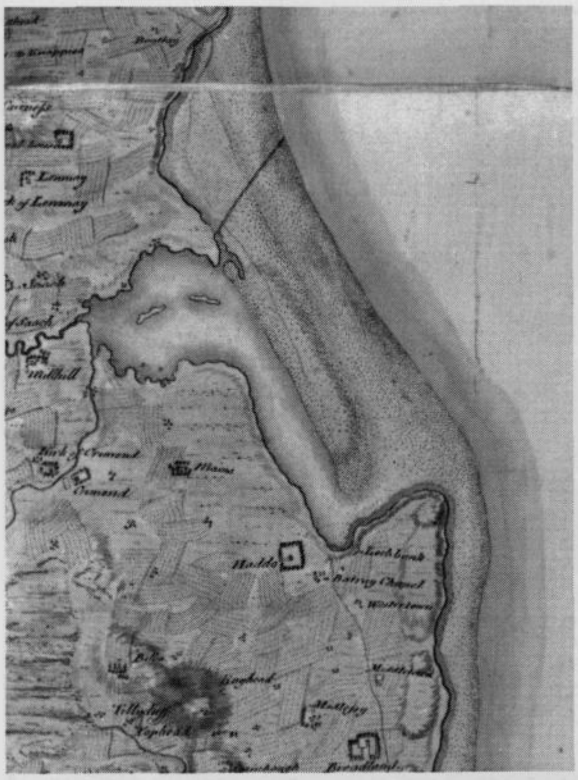

Figure 7.35 The Loch of Strathbeg, as mapped in 1755 by the military surveys of William Roy. Note the loch exit is located in the south, but also that an artificial channel across the north end of the beach was in existence to allow the loch to drain northwards. (Photograph © The British Library from the British Library Special Collections, Maps C9b 31.)

tinctive lower relict cliff forms the western margin of the present Loch of Strathbeg and Walton (1956) interprets this cliff as representing the margin of a later, possibly mid-Holocene, sea level at 5 m. The ridges of a gravel spit began to extend from the north to partially enclose a tidal lagoon with a narrow inlet (*c.* 45 m wide) between the southernmost limit of the gravel bar and the relict cliff near Old Rattray (Figure 7.32) (Walton, 1956; Ritchie *et al.*, 1978). The later arrival of sand encouraged the development of the sand-dune complex.

Archaeological and historical evidence documents the final closure of the bay of Strathbeg. The tidal inlet of Strathbeg, sheltered from the open coast by the extensive gravel spit and overlying dunes, provided an obvious natural harbour and it is not surprising that a small coastal fishing village developed (Figure 7.35). The earliest evidence of settlement at Rattray dates to around the end of the 13th century (Walton, 1956) and during the 16th and early 17th centuries the harbour at Strathbeg flourished (Walton, 1956). However, the inlet was almost certainly shallowing over time and as early as 1654 there is evidence that the exit was threatened by sand deposition (Gordon, 1843). The final closure of the bay is thought to have occurred by the deposition of windblown sand during a storm in the 1720s (Walton, 1956). The final sealing of the inlet was apparently so sud-

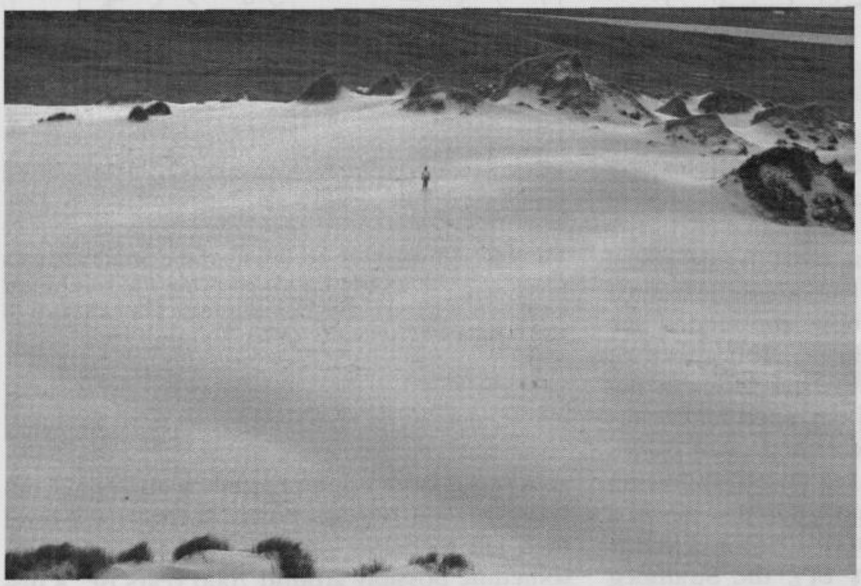

Figure 7.36 A large coalesced blowthrough in the southern part of Strathbeg. The loch is visible in the top right. The figure provides the scale. (Photo: J.D. Hansom.)

den that a vessel is reputed to have been trapped within the harbour and its impounded cargo of slates then used to roof a nearby house at Mains of Haddo (Walton, 1956). Roy's map of 1747–1755 shows the enclosed Loch of Strathbeg with a new outlet at the north end of the lagoon (Figure 7.35). The decline of the settlement of Rattray followed and it had ceased to exist by the middle of the 18th century (Walton, 1956). At the end of the 18th century the high water-level of the Loch of Strathbeg threatened inundation of agricultural land and led to an artificial outlet channel being cut through the gravel bar (Walton, 1956). Since then this artificial cut has been maintained.

Since the final closure of the Loch of Stathbeg there has been over 1 km of sand accretion to seaward, involving the development of an extensive dune system consisting of numerous parallel linear dune ridges (Walton, 1956; Ritchie *et al.*, 1978; Ritchie, 1983). Dune morphology suggests that the dune ridges developed at the rear of a wide beach, which then abutted the emerged gravel bar and spit features (Ritchie *et al.*, 1978). Such processes have their modern counterparts, particularly at the outlet of the loch in the north–centre part of the bay, where young embryo and foredune ridges are developing seawards of the main dune ridge, although net sand drift is now considered to be low (Ramsay and Brampton, 2000d). Dune face erosion is largely confined to the north end of the beach although there is also a zone of active wave undercutting in the extreme south where erosion has produced high sand cliffs (Ritchie *et al.*, 1978). Elsewhere, the coastal edge tends to undergo cyclic seasonal effects of dune undercutting in winter and accretion in summer (Ramsay and Brampton, 2000d). Away from the major blowthrough corridors and deflation areas in the south (Figure 7.36), there is either minor aggradation or stablility, as occurs on the inland dune surfaces (Ritchie *et al.*, 1978).

Strathbeg provides one of the best examples in Scotland of a suite of parallel linear dune ridges with intervening depressions produced by progradation. These progradational processes also contributed to the final isolation of the Loch of Strathbeg and remain active today, particularly around the loch outlet. It is apparent from the above discussion that although the general evolution of this area has been interpreted (Walton, 1956) there remain substantial gaps in our knowledge and the exact sequence and chronology of the geomorphological evolution of Strathbeg remains uncertain. In addition, the spectacular erosional forms in the southern part of the dune system present a valuable opportunity to assess the processes and forms of erosion in a large-scale dune system.

Conclusions

The extensive and varied dune morphology of Strathbeg is of outstanding geomorphological interest. The site contains excellent examples of parallel linear dune ridges, with up to 18 separate dune crests and intervening depressions between the outer beach and the freshwater Loch of Strathbeg some 1.2 km inland. The progradational processes that created this suite of linear dunes remain active today. The dune system overlies a base of emerged gravel ridges, which were originally responsible for the partial closure of the inland loch. The southern part of Strathbeg contains spectacular examples of wind erosional processes in large-scale coastal dunes, and the relatively undisturbed nature of the Strathbeg dunes enhances the scientific interest of the site.

FORVIE, ABERDEENSHIRE (NK 020 270)

J.D. Hansom

Introduction

The Sands of Forvie, north-east Scotland (see Figure 7.1 for general location), form the fifth-largest and least-disturbed sand-dune system in Britain (Dargie, 2000). This vast site covers 810 ha and contains a remarkable assemblage of blown-sand landforms, some of which are unique in Britain, for example, the classic parabolic dunes at north Forvie and the unvegetated sand dunes of south Forvie. Others are representative of much of the dune coastline of north-east Scotland. The mode of evolution of the Sands of Forvie has sparked much scientific debate (e.g. Landsberg, 1955; Kirk, 1955; Steers, 1973; Walton and Ritchie, 1972; Ritchie, 1992). Early work suggested a series of large sand waves migrating successively from the south end of the peninsula to the north end

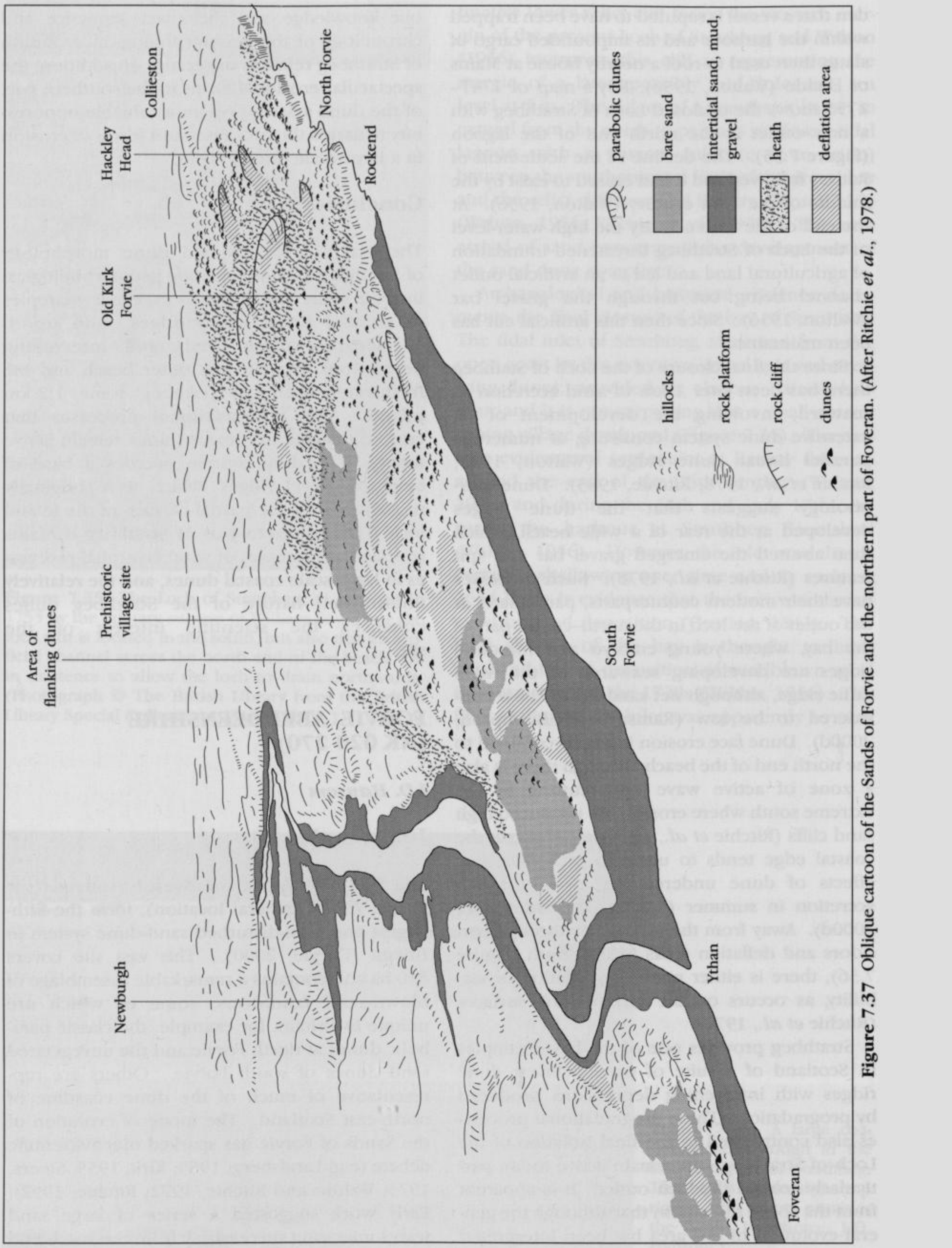

Figure 7.37 Oblique cartoon of the Sands of Forvie and the northern part of Foveran. (After Ritchie *et al.*, 1978.)

Figure 7.38 Extensive areas of bare sand are visible in this oblique aerial view of Forvie and Foveran looking north along the axis of the Ythan estuary. In the middle right of the image, the large unvegetated dune of South Forvie allows sand to traverse the peninsula from the North Sea intertidal area in the east to the inner Ythan estuary in the west. In addition, sand still moves northwards from South Forvie but at a much smaller scale than in the past. These former sand movements contributed to the migration and development of several large parabolic dune systems that now rest on the higher ground of north Forvie. (Photo: P. and A. Macdonald).

of north Forvie (Landsberg, 1955). Although archaeological evidence supports a northerly migration of sand (Kirk, 1955; Ralston, 1983), the pattern proposed by Landsberg has been modified (Steers, 1973; Walton and Ritchie, 1972; Ritchie, 1992) in favour of a more complex theory of the 'scatter and break-up' of the northward migrating sand waves as they mount the higher altitudes of the north Forvie plateau.

Description

The Sands of Forvie (Figure 7.37) cover 810 ha of land in a triangular shape to the north and east of the River Ythan. The region can be differentiated on the basis of geology and dune morphology on a north–south basis. North Forvie is characterized by an underlying till-covered rock platform sloping north to a height of 57 m OD, which is surmounted by a series of discontinuous dunes together with parabolic dunes facing west and south-west. The coastline of north Forvie comprises rock and till cliffs, which reach 40 m OD towards Collieston. Lying between the Ythan estuary and the North Sea, south Forvie is essentially a sand peninsula, with sand dune complexes, dynamic sandhills and sand waves running along a north–south alignment. A series of low ridges of glacial deposits and emerged beaches reaching 12 m OD underlie the south Forvie dunes. In the extreme south, intertidal and aeolian processes at the mouth of the Ythan estuary ensure a continuous supply of sand to the northward encroaching sand waves which dominate this area (Figure 7.38). Foveran, the area of dunes to the south of the estuary, is an integral part of the system in terms of sediment transfer and supply and, as such, is included within this large GCR site. The geomorphology of these three main areas is described below.

North of Rockend, Forvie is characterized by an underlying till-covered rock platform sloping north to a height of 57 m OD and surmounted by a series of discontinuous dunes and parabolic dunes. Ritchie (1992) describes the west- and south-west-facing parabolic dunes of north Forvie as good examples of this type of landform, although notes that the mode of development differs from the classic textbook form. Nine parabolic dune complexes can be identified in north Forvie (Figure 7.39). To the north of Hackley Bay, a group of three (3, 4 and 5 with orientations of 237°, 242°, 230°) form part of an area of composite forms of high dunes and dune ridges. In the central and western part of the plateau lie a detached group of four parabolic dunes (6, 7, 8 and 9, with orientations of 173° 200°, 203°, 168°) together with a further two parabolic dunes (1 and 2 with orientations 251°, 211°). The orientation of the parabolic dunes contrasts markedly with the main active blowthrough orientations of the coastal dunes (which lie between 120° and 140°) and the

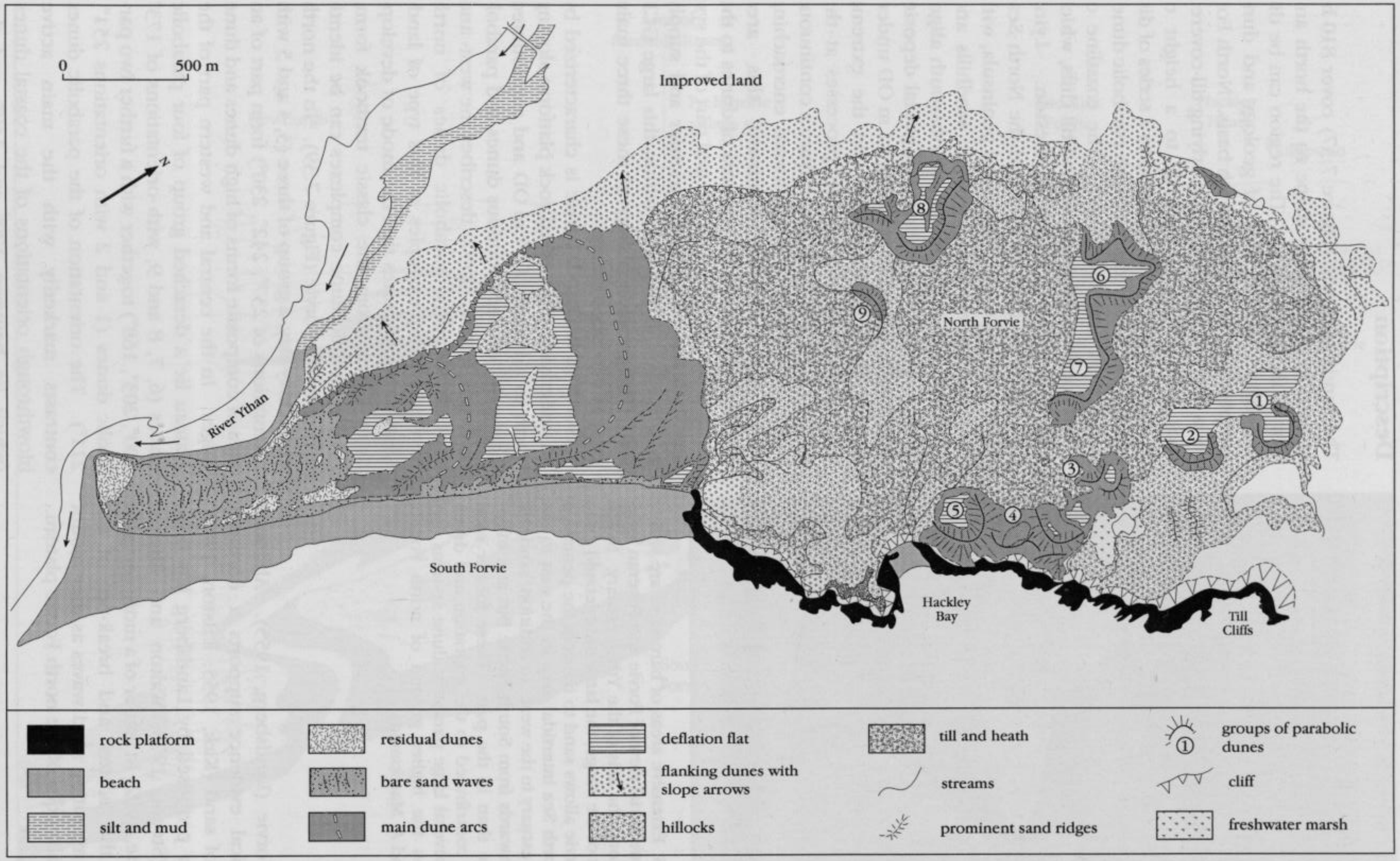

Figure 7.39 The coastal landforms of the Sands of Forvie showing the bare sand and dune-arc dominated southern part, and the largely stabilized and vegetated northern part, which also hosts the nine groups of parabolic dunes. (After Ritchie *et al.*, 1978.)

general south–north migration direction of the great sand arcs of south Forvie (Ritchie, 1992). The extensive dune surfaces of north Forvie are mostly vegetated by acidic heaths growing over a thin sand veneer that is often less than a metre thick. The flanking dunes that form the western edge of south Forvie continue into north Forvie and have actively eroding and dissected east-facing slopes that in places merge with the parabolic dune complexes described above.

South of Rockend (Figure 7.37) the massive sand peninsula of south Forvie is underlain by low ridges of glacial deposits and emerged beaches, fronted in the east by an active beach and limited in the west by the tidal estuary of the River Ythan (Figures 7.37–7.39). Marking the southern end of south Forvie is a series of dynamic spits and bars where the River Ythan enters the North Sea. South Forvie is a large sand-dune system characterized by an outer zone of active coastal dune ridges and an inner zone of great sand arcs. The active coastal dunes of south Forvie range in height from 2 to 15 m and are all dissected to varying extents. Several large V-shaped blowthroughs occur and some of the dune ridges have been completely removed by deflation. Detailed study reveals that most of the foredune face at south Forvie shows a high degree of instability characterized by general retreat and erosion (Esler, 1976, 1983), although it is unclear whether this represents a long- or short-term trend.

The exceptional, and perhaps the most distinctive, feature of south Forvie is the great dome of bare sand that covers the south end of the peninsula (Figure 7.40). This extensive ridge of sand is more than 1 km long, 200 m wide and over 25 m high; it dominates the south Forvie peninsula. Surface instability is indicated by an absence of vegetation and the occurrence of sand-wave and ripple forms that trend in a south to north direction. However, active sand transport occurs not only northwards onto the adjacent deflation plain, but also westwards towards the Ythan estuary where it cascades down steep unvegetated slopes into the estuary and enters a semi-closed sediment circulation cell described by Wetherill (1980).

The central and northern parts of south Forvie consist of three very large arcuate sand ridges that extend across the entire width of the peninsula. The southern arc is 500 m wide and 20 m high, while the northern arc is *c.* 1500 m wide and exceeds 35 m high. In detail, the surfaces are very complex features with a series of vegetated dune ridges and bare deflation

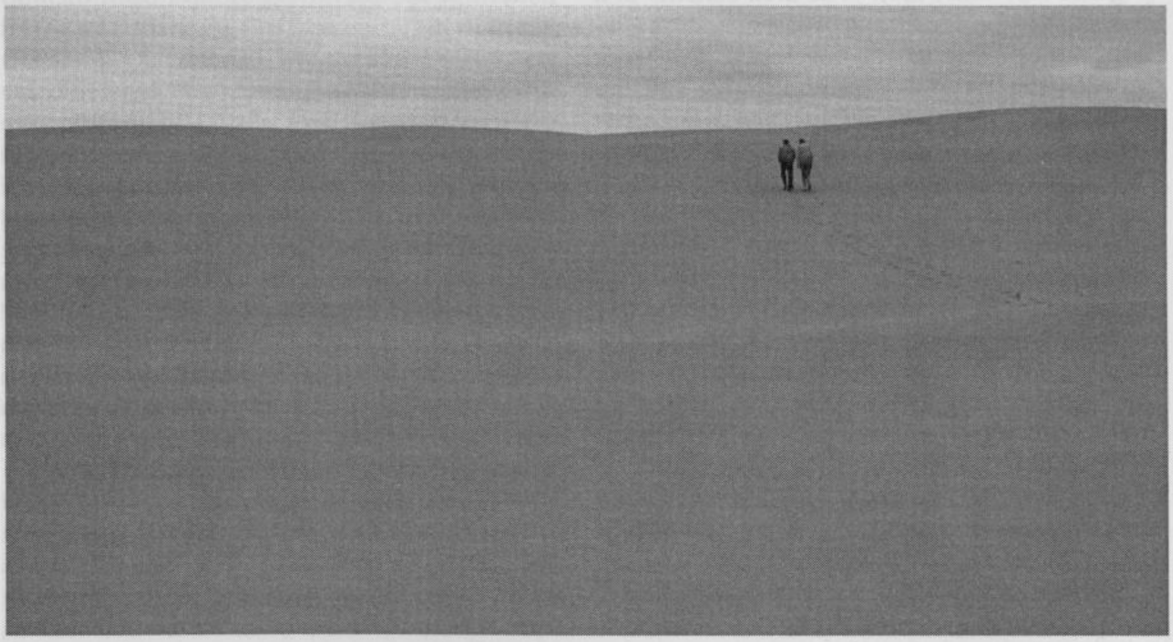

Figure 7.40 The great dome of bare sand that dominates south Forvie is subject to active aeolian activity and sand movement. (Photo: J.D. Hansom.)

surfaces superimposed onto the main form. Parts of the south-facing slope are often severely deflated, particularly on the western side where the underlying till basement is exposed. Erosional forms (such as deep linear blowthroughs and V-shaped hollows) at various stages of activity are common. Functionally linked to the processes and forms of wind erosion are a series of depositional forms, the best example of which is a mass of bare sand that spills northwards from the north-west side of the northern arc, as a steep sand slope. These massive sand arcs are subject to rapid change and a detailed study of the northern arc showed a complex series of rapid alterations from vegetated to unvegetated status within a decade (Wright and Harris, 1988).

On the eastern side of south Forvie, the sand arcs meet the coastal dunes causing higher dune elevations that are termed 'nodes' by Ritchie *et al.* (1978). The western margin of south Forvie consists of flanking dunes with steep, eroding and actively dissected east-facing slopes, and stable, concave western slopes that grade steeply down to an emerged beach terrace above the tidal flats of the estuary.

South of the Ythan lies Foveran, a further area of beach and dunes is included within the GCR because of the intrinsic geomorphological interest and since it feeds sediment northwards into the south Forvie system and beyond (Figures 7.37 and 7.38). The area consists of a series of sub-parallel lines of massive, 10–12 m-high dunes with a well-developed wet slack between the broad coastal dune ridge and the sand-covered Holocene cliffline, which lies a few hundred metres inland. Low cliffs cut into glaciogenic deposits and emerged ('raised') beach deposits are conspicuous features underlying much of Foveran. The beach comprises a series of shore-parallel intertidal bars with intervening runnels whose migration has deflected small streams northwards. At the Ythan exit the northward drift has resulted in accretion so that the beach is now 250 m wide and backed by actively accreting embryo dunes (MacTaggart, 1998b).

In contrast to this essentially accreting area close to the Ythan exit, the area to the south is characterized by a discontinuous and severely undercut foredune. High eroded dune faces are produced along the seaward edge and extensive unvegetated sand aprons have accumulated between and behind the eroding dunes, indicating significant movement of sand landwards. At the north end of the beach, concrete anti-tank blocks dating from the 1940s are partially exposed by erosion of the coastal edge. Since these traps have been buried by sand accumulation prior to exhumation, then at least one cycle of accretion followed by erosion is suggested. Progradation in the north-east is suggested by the occurrence of a zone of stable dunes up to 25 m high fronted by foredunes that reach 21 m in width. Probably the most distinctive landform at Foveran is an extensive area of bare sand that extends 0.5 km inland from the northernmost fragmented foredune ridge. Ritchie *et al.* (1978) consider this area to be comparable to the more extensive bare sand area at south Forvie, its scale and height being partly determined by undulations in the underlying glaciogenic landforms and emerged, marine, gravel ridges. However, sand passing through breaches on the foredune ridge continues to migrate upslope in a northerly and north-westerly direction.

Interpretation

It is uncertain when the dune system at Forvie first began to develop (Stapleton and Pethick, 1996), although archaeological evidence indicates that blown sand accumulations existed near the south end of south Forvie about 5000 years BP (Ralston, 1983). The distribution and pattern of the Forvie dunes have been the subject of intermittent research since the pioneering vegetation study of Landsberg in 1955. Landsberg (1955) postulated an evolution whereby the great arcs of dunes, including the northern group of parabolic ridges, spread northwards from the beach, bar and spit sand sources of the mouth of the River Ythan. Sand also fed into the system from the extensive North Sea beaches on the east side of the south Forvie peninsula. Landsberg (1955) identified seven arcs of sand accumulation in the region and postulated that each wave of sand formed in the south and moved northwards at a migration rate which decreased progressively to the north as a result of vegetation colonization.

Although there is evidence for a chronology of sand drifting northwards (Landsberg, 1955; Kirk, 1955; Ralston, 1983), the hypothesis of a series of northward migrating dunes has since been rejected (Steers, 1973; Walton and Ritchie, 1972; Ritchie, 1992). The formation of new sand waves to the windward of a pre-existing wave would deprive the latter of aeolian sand, leading to vegetation colonization and dune stabilization. In addition, there is only patchy morphological, historical and archaeological evidence of recognizable sand waves or sand arcs in north Forvie and so the assumption of a consistent south to north aeolian transport mechanism is likely to be over-simplified and takes little account of the dune morphology at south Forvie.

Walton and Ritchie (1972) and Ritchie (1992) suggest that whereas south Forvie may have developed in a similar manner to that proposed by Landsberg (1955), north Forvie developed by a process of 'scatter and break-up'. This envisages sand moving from south Forvie into north Forvie as a series of events with a strong northerly component to form discrete and separate dune complexes (Figure 7.39). The series of dunes and dune ridges became increasingly isolated as the sand was forced onto the higher altitudes and more open topography of the northern plateau (Ritchie, 1992). The dunes that form the groups of parabolic dunes (Figure 7.39) are thought to have been fed by the periodic migration of sand from the north end of the south Forvie peninsula. A major influx seems to have occurred in 1413 when the Old Kirk of Forvie near Rockend and the surrounding cultivation rigs are known to have been abandoned (Ritchie *et al.*, 1978). Following this major influx, the dunes spread rapidly northwards, progressively infilling two lochs in the 18th and 19th centuries (Figure 7.41) and, as chronicled by Landsberg (1955), encroached on to farmland at Collieston around the end of the 18th century. However, the orientations of the parabolic dunes of north Forvie suggest a swing towards the east as the dunes migrated and stabilized, possibly due to vegetation colonization as the water table was exposed.

Today sand continues to spill northwards on the north-west side of the south Forvie peninsula (Wright and Harris, 1988), providing present-day analogues for past processes. The active sand movement in the north part of south Forvie suggest that similar areas were locally active in the past, providing pulses of sand that drifted onto parts of the north Forvie plateau. Separate pulses, in time and space, would facilitate the development of discrete masses of sand to then evolve into detached parabolic systems and other sand dune complexes (Ritchie, 1992).

Detailed studies on the dynamics of the Ythan estuary (Stove, 1978; Wetherill, 1980) demonstrate that the sand peninsula and dome of bare sand of south Forvie forms part of a semi-closed sediment circulation cell. This involves east to west aeolian transport of sand over the dune and into the estuary. River flow and ebb tides carry the sand onto the estuary mouth spits and bars for transport back onto the beach. Based largely on cartographic evidence, Wetherill

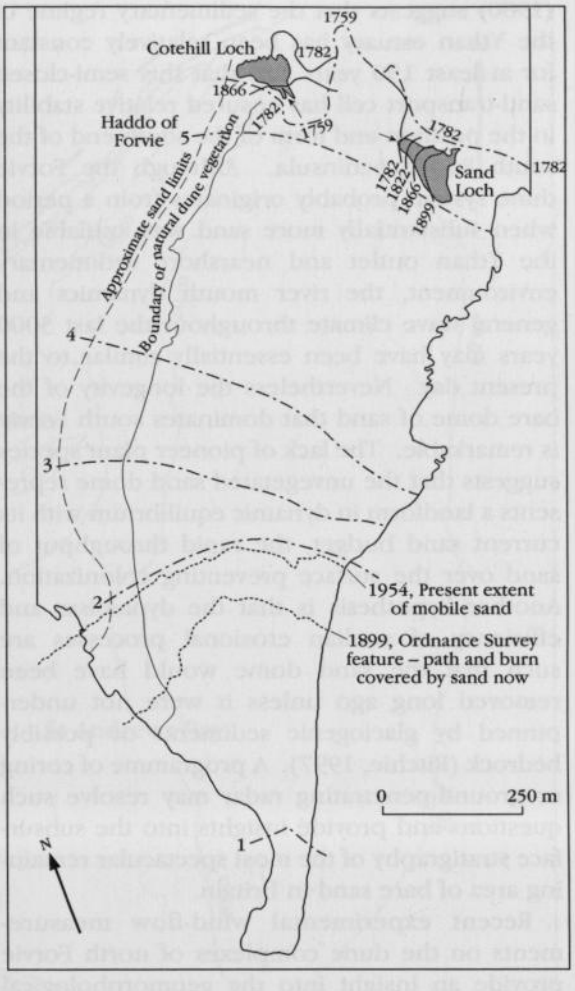

Figure 7.41 The postulated phases of sand movement over Forvie. The lines relate to sand limits as follows: 1 = the northern limit of sand before about 0 BC; 2 = the sand limit a few hundred years after 0 BC (there was little further northward encroachment until at least the 8th century AD); 3 = the limit of the area inundated by sand early in the 15th century; 4 = position of the sand front by the end of the 15th century; 5 = line reached by 1688. Further small advances are shown by dated boundaries. (After Ritchie, 1992.)

(1980) suggests that the sedimentary regime of the Ythan estuary has been relatively constant for at least 150 years and that this semi-closed sand-transport cell has ensured relative stability in the position and form of the south end of the south Forvie peninsula. Although the Forvie dune system probably originates from a period when substantially more sand was available in the Ythan outlet and nearshore sedimentary environment, the river mouth dynamics and general wave climate throughout the last 5000 years may have been essentially similar to the present day. Nevertheless the longevity of the bare dome of sand that dominates south Forvie is remarkable. The lack of pioneer plant species suggests that the unvegetated sand dome represents a landform in dynamic equilibrium with its current sand budget, the rapid throughput of sand over the surface preventing colonization. Another hypothesis is that the dynamism and efficiency of aeolian erosional processes are such that the sand dome would have been removed long ago unless it were not underpinned by glaciogenic sediments or possibly bedrock (Ritchie, 1997). A programme of coring or ground-penetrating radar may resolve such questions and provide insights into the subsurface stratigraphy of the most spectacular remaining area of bare sand in Britain.

Recent experimental wind-flow measurements on the dune complexes of north Forvie provide an insight into the geomorphological processes of parabolic dune development (Robertson-Rintoul, 1985, 1990). The development of wind jets at crestal locations probably limits dune height, with eddies important on steep leeside and windward slopes affecting forward sand movements. Spiral vortex flows along the windward arms are likely to be responsible for lateral expansion of the parabolic dune.

The Sands of Forvie form the fifth-largest and least-disturbed sand-dune system in Britain (Ratcliffe, 1977). The blown-sand morphology of north Forvie is unique in Britain, with massive sand hills and dune complexes on the high rock plateau that appear to have migrated from the south. It is this unique evolution, which is not fully understood, that is of outstanding geomorphological interest and warrants the inclusion in the GCR. In addition, the parabolic dune forms of north Forvie are spectacular landforms (Ritchie, 1992). They provide an interesting contrast to the textbook formation displayed by the parabolic dunes at Barry Links and Morrich More. The dynamic interchange of sediment between the dunes of south Forvie and the extensive sand beach and spit complex at the mouth of the River Ythan add to the geomorphological interest of the site.

Conclusions

The Sands of Forvie represent a classic site for coastal geomorphology. The remarkable assemblage of windblown landforms, some of which are unique while others are representative of much of the dune coastline of north-east Scotland, are of outstanding scientific interest both individually and as an assemblage, and provide an excellent field site for innovative research at a variety of scales. The mode of evolution of this vast system, with huge volumes of sand migrating northwards from the 'normal' sand-dune complex of south Forvie onto the high rock-plateau of north Forvie, is unique. The parabolic dune forms of north Forvie are classic landforms that have developed in a different way to the classic textbook descriptions and this enhances their scientific interest.

BARRY LINKS, ANGUS (NO 550 320)

J.D. Hansom

Introduction

The Barry Links dune system has developed on an extensive broad triangular foreland (*c.* 11 km^2) on the northern side of the Firth of Tay, eastern Scotland (Figure 7.42). Although Barry Links contains representative examples of many beach, dune and links landforms, it is the exceptional series of well-developed parabolic dunes that is of outstanding geomorphological significance. Parabolic dunes are relatively rare in the Scottish coastal dune environment and are extensively developed in only three areas: Barry Links, Sands of Forvie, and Morrich More. The parabolic dunes of Barry Links are unique in that they have a pronounced V-shaped form with a mean length-to-width ratio of 3.3, compared to the more U-shaped forms of the dunes of Forvie and Morrich More (see GCR site reports), with ratios of 1.2 and 2.0 respectively (Ritchie, in MacTaggart, 1997b). The Barry Links parabolic dune systems have spectacular, elongated,

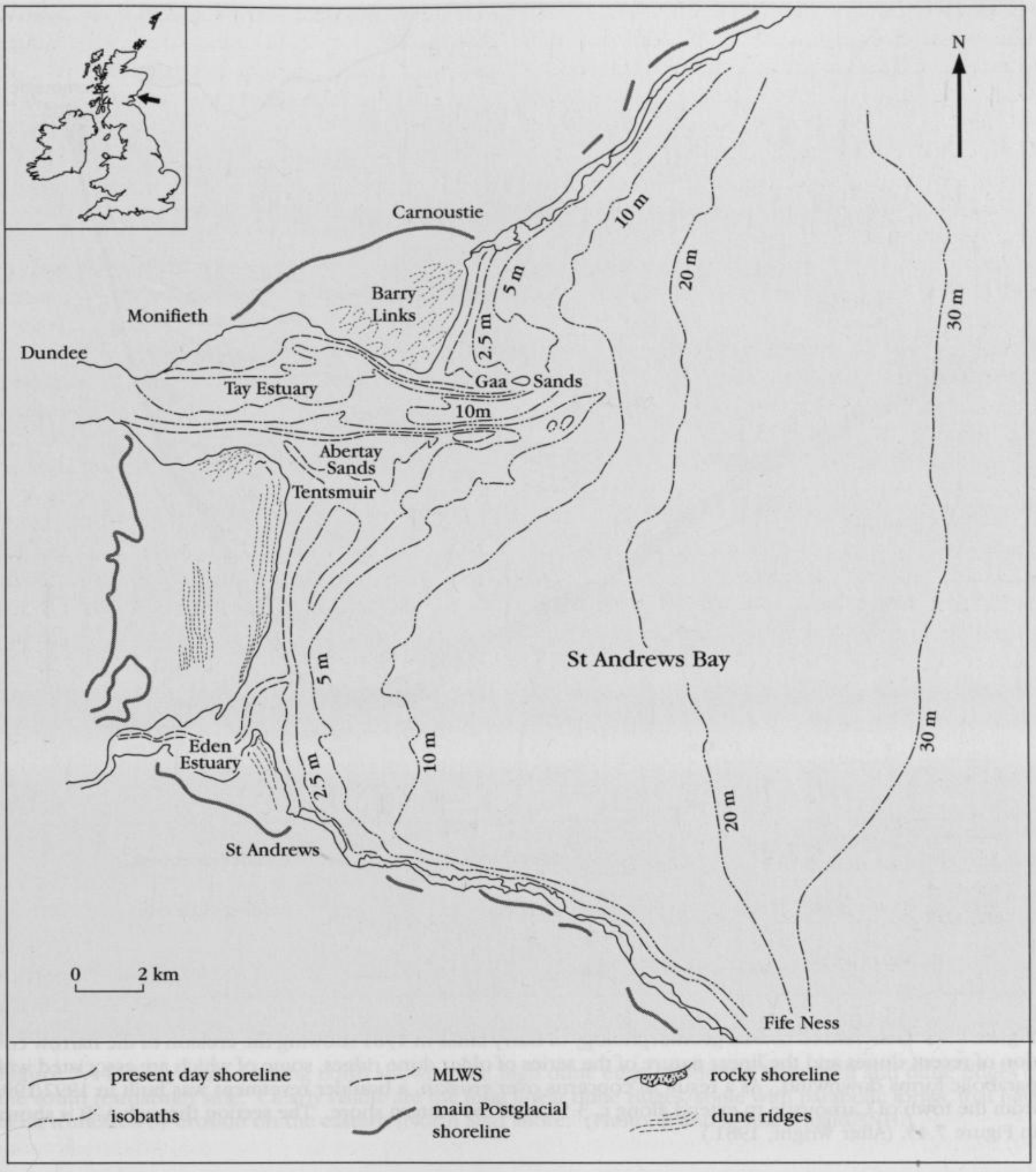

Figure 7.42 Location of Tentsmuir and Barry Links in St Andrews Bay. Tentsmuir and Barry Links have built out eastward of the main Postglacial (Holocene) shoreline at the mouth of the Tay estuary. Extensive intertidal and subtidal sand banks have also accreted at Abertay and Gaa Sands in the zone where river discharge interacts with open coast tides and waves. (After Ferentinos and McManus, 1981.)

hairpin shapes that are unique in Britain. The geomorphological features of Barry Links complement those of the Tentsmuir dune system to the south of the estuary, which is also of outstanding scientific merit (see GCR site report).

Description

The extensive sand-covered triangular foreland of Barry Links juts out on the northern side of the Firth of Tay, on the east coast of Scotland

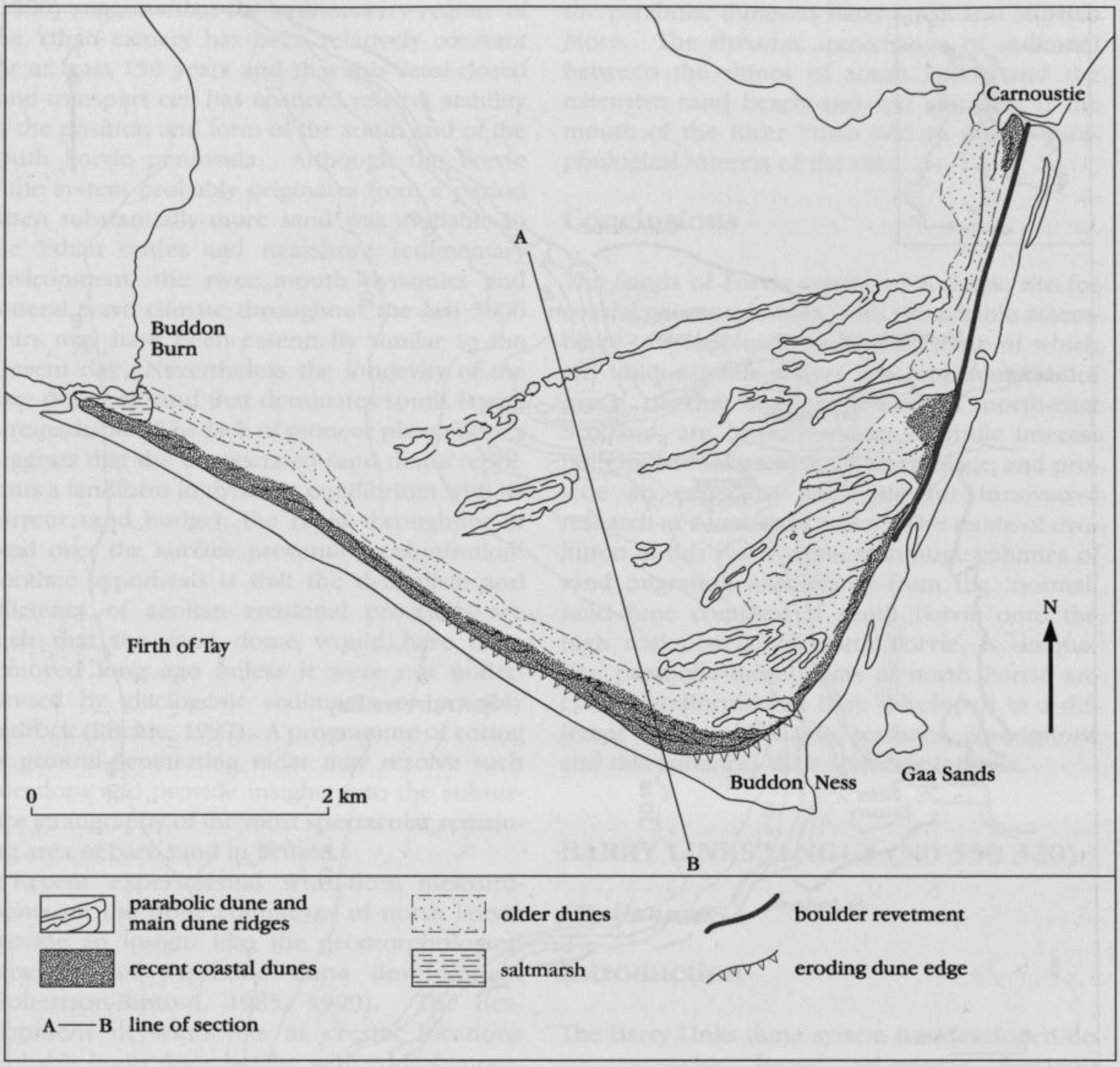

Figure 7.43 Generalized coastal geomorphology of Barry Links in 1981 showing the erosion of the narrow cordon of recent dunes and the linear nature of the series of older dune ridges, some of which are associated with parabolic forms downwind. As a result of concerns over erosion, a boulder revetment was built in 1992/1993 from the town of Carnoustie to extend along c. 3.5 km of the eastern shore. The section through A–B is shown in Figure 7.45. (After Wright, 1981.)

(Figures 7.43 and 7.44). Two 4.5 km-long sand beaches converge at Buddon Ness at the southern tip of the foreland with the extensive intertidal sandbanks of Gaa Sands, submerged during most of the tidal cycle, lying to the east of Buddon Ness (Figure 7.43). Both the east-facing and estuarine (south-facing) beaches are composed of medium-grade, non-calcareous sand ($D_{50} = 0.24$ mm) with occasional patches of gravel. The foreshore of the east-facing beach is *c.* 300 m wide, and flat with several intertidal shore-parallel bars. The extensive northern coast has a history of severe erosion, the dune face recorded to have retreated up to 10 m in one year (Wright, 1981). Early attempts in 1978 to combat erosion using gabions were rapidly overridden and the later 'solution' of 1992–1993 was to place rock armour on the beach and dune face along a *c.* 3.5 km length of coast (Hansom, 1999). Although aesthetically unattractive the

Figure 7.44 Barry Links looking north showing the high dune edge at Buddon Ness itself and dune ridges of the south (estuarine) side. Clearly visible are the long linear dune ridges, some with parabolic forms, that have been truncated by erosion on the eastern (North Sea) shore. (Photo: P. and A. Macdonald/SNH.)

rock armour appears to be serving its purpose of preventing further erosion along the protected stretch of coast and by 1994 there were no signs of slumping of the rock surface (ASH Consulting Group, 1994). However increased scouring at the toe of the armour combined with the loss of sand supply to the backshore from the now inactive dune face may have resulted in lowering of the backshore (ASH Consulting Group, 1994).

At the southern end of the rip-rap, an erosional bight has resulted in 50 m of recession landward of the rip-rap alignment and erosion extends to within 100 m of the Ness itself (Hansom and Rennie, 2003).

To the north of the point at Buddon Ness there are areas of local coastal accretion (Wright, 1981) where pioneer vegetation is colonizing the blown sand on the backshore. At Buddon Ness itself, where erosion appears to dominate, the beach is markedly steeper (7–8°) and narrower. Historically, the coastline around Buddon Ness has undergone considerable change (Wright, 1981), which is not surprising on account of its sensitive location at the point where the south-facing estuarine coastline changes to an open North Sea orientation. Local evidence shows considerable fluctuations in the position of the coastline. For example, by the early 19th century the site of the original Buddon Ness lighthouse, which was located on the southern extremity of the point during the early 16th century, was 6 m under water and 2 km to the south-east of the current one (Wright, 1981). West of Buddon Ness the beach is narrower (200 m) and lacks some of the morphological variety of the North Sea coast. The backshore is steeply sloping and fronts a foredune that has both actively accreting and eroding sections.

A series of long, narrow, well-vegetated coast-parallel dune ridges back the estuarine (south-facing) beach. The coastal dunes are 5–11 m high at Buddon Ness and decrease in height westwards, lowering to 1–2 m near the Buddon Burn. The topography of this coastal dune system is complex. Towards the western end of the shoreline for a distance of *c.* 2 km there are three clearly defined sub-parallel dune ridges. Farther east the dune ridges are characterized by old blowthroughs and associated re-depositional sandhills. Close to the point of Buddon Ness this mature dune complex is fronted by a relatively narrow line of actively accreting dunes (Figure 7.43). The single coastal dune ridge along the east-facing North Sea coast has a more varied morphology. Severe wave erosion has caused relatively rapid retreat along most of this length of coastline, although recent protection works along the northern 3.5 km stretch of coastline have effectively stopped activity in this part of the eroding dune face (see above). The vegetated coastal dune ridge is discontinuous with signs of intermittent marine breaching. A complex, high relief dune morphology has developed where the parabolic dune arcs of the interior coalesce with the coastal dune ridge. The relative proximity of several of the inland parabolic dunes to the eastern coastal edge (Figures 7.43 and 7.44) poses an interesting question concerning the relative importance of coastal retreat and the eastwards migration of the parabolic arcs in producing the truncated high dune cliffs characteristic of this coastline.

Inland from the coastal dunes is an extensive area of low undulating vegetated links (generally under 6 m OD) covering most of the triangular foreland of Barry Links. A well-developed system of parabolic dunes (Figures 7.43 and 7.44) has developed on this undulating links topography. The parabolic dunes of Barry Links are unique in Britain with a well-developed and pronounced V-shape. These dunes are long and narrow with a fairly regular outline in plan view and the extent to which secondary blowthrough development has occurred is minimal. The pattern of dune forms on Barry Links displays an unusual degree of regularity. Two distinctive morphological attributes contribute to this relatively ordered appearance. Firstly, the measured length-to-width ratios are closely and evenly distributed about the mean value of 3.3 for the dune system and, secondly, the dune orientations as represented by the directions of their long axes are remarkably uniform (Figure 7.44). The 243° orientation of the Barry parabolics suggest that they have migrated in the past from the south-west to north-east, towards the eastern coastline.

The Barry parabolic dunes are now almost completely vegetated and stabilized, with the exception of the large dune that is utilized by the Ministry of Defence (MOD) as a firing range. In the northern part of the foreland the parabolic dunes stand as discrete units. Towards the south, in the vicinity of Buddon Ness, some adjacent dunes overlap although this does not appear to disrupt the general parabolic shape. Some breaks in the orderly dune pattern occur at the southern and eastern margins of the foreland, where some of the parabolic dunes have intersected the present-day coastline. The convergence of the parabolic dunes with the coastal dune ridges has resulted in the production of a high relief and complex dune topography. Isolated SW–NE-trending elongated dune ridges suggest coastal erosion has truncated a former, more extensive, system of parabolic dunes.

Interpretation

The evolution of the large foreland of Barry Links remains speculative. Its general triangular shape, comparable to accumulation features in southern England such as Dungeness, Kent (see GCR site report in Chapter 6), suggests that the area has developed as a result of extensive deposition of beach materials in the past. There

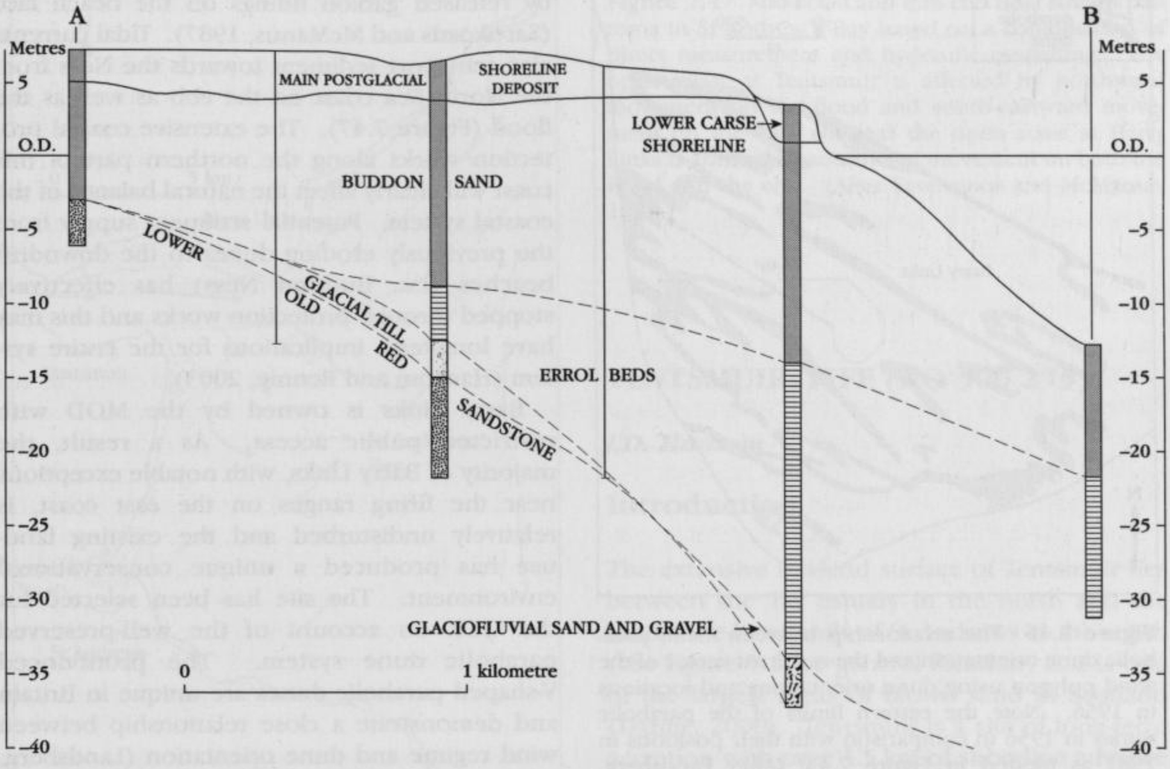

Figure 7.45 Stylized 3.5 km cross-section (along the line A–B on Figure 7.43) of Barry Links and Buddon Ness as reconstructed from borehole data. Barry Links sits atop substantial thicknesses of marine and shoreface deposits and suggests that this estuary-mouth site has undergone continued deposition over much of the Holocene Epoch. (After Paterson, 1981.)

appears to be little doubt that, as with much of the North Sea coast of Scotland, large parts of the foreland consist of emerged beaches. Steers (1973) posed the question of the stability of this distinctive triangular foreland. Analysis of old maps of the area covering the last 200 years show change only at the margins, suggesting that the main body of the feature is based on a more stable foundation, possibly an ancient beach or rock platform (Steers, 1973), although there is no surface indication of underlying rock. Borehole evidence (Figure 7.45) suggests that beneath the dunes lies a series of emerged shorelines cut into a thick sequence of marine sands (Buddon Sand) which themselves overlie marine clay (Errol Beds) (Paterson, 1981). The physiographical evolution of Barry Links clearly requires further investigation, particularly in the context of changing relative sea levels.

The parabolic dune system of Barry Links is one of the finest and well-developed in Britain, but there has been surprisingly little research carried out on these spectacular forms. Early work by Landsberg (1956) shows that wind regime is a major factor in the orientation of the Barry dunes (Figure 7.46). Each wind direction in proportion to its sand-moving power was plotted and the resultant vector (shown by the arrow on Figure 7.46) completes the wind direction polygon and indicates the direction of the dominant wind effect. This resultant vector conforms almost exactly with the mean dune orientation of the Barry dunes (Landsberg, 1956). The open exposure of the Barry Links foreland and the lack of topographical interference with formative winds from the south-west may explain the regular form, orientation and pattern of the Barry Links parabolic dunes (see Figure 7.44). The undulating links surface is remarkably even; the parabolic dunes that have developed on this sandy plain represent the primary relief features in the area so, in the Scottish

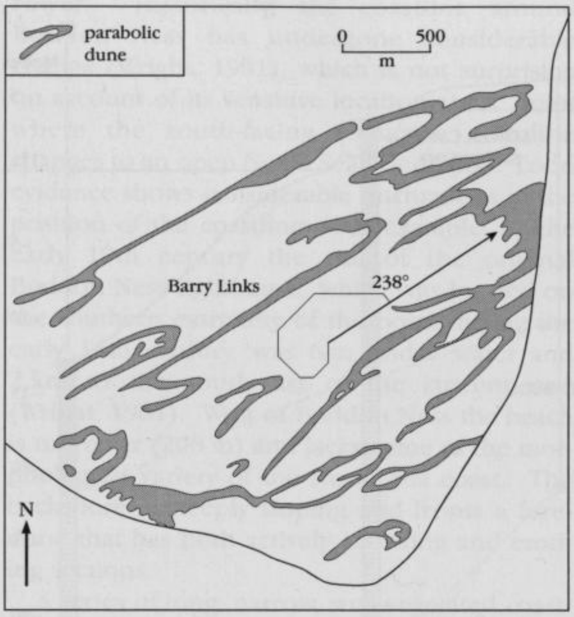

Figure 7.46 The relationship between mean parabolic dune orientation and the resultant vector of the wind polygon using dune orientations and locations in 1956. Note the eastern limits of the parabolic dunes in 1956 in comparison with their positions in 1981 as plotted in Figure 7.43. (After Landsberg, 1956, from Hansom, 1988.)

context, the wind regime is unusually free from topographic effects. In addition, the Barry parabolic dunes lack the complications of subsurface control, a common feature of many coastal dune systems (e.g. Machir Bay). This may also help explain the orderly form of the Barry parabolic dunes. Map and field evidence shows an apparent migration of the dune forms towards the eastern coastline. However the present stability of the dunes suggests that this, certainly in the recent past, may be more a result of rapid marine erosion in the east, rather than the recent downwind migration of the dunes themselves (compare Figures 7.43, 7.44 and 7.46).

Potential patterns of longshore sediment transport on the coasts north and south of the Tay estuary have been calculated using wave refraction modeling (Sarrikostis and McManus, 1987). The model predicts a south-westerly drift down the exposed North Sea coast of Barry Links to Buddon Ness, where deposition occurs. Field evidence appears to support this model; the southward transport of material from Carnoustie to Gaa Sands has been demonstrated by released gabion fillings on the beach face (Sarrikostis and McManus, 1987). Tidal currents also transport sediment towards the Ness from the North Sea coast on the ebb as well as the flood (Figure 7.47). The extensive coastal protection works along the northern part of this coast will clearly affect the natural balance of the coastal system. Potential sediment supply from the previously eroding dunes to the downdrift beaches (i.e. Buddon Ness) has effectively stopped through protection works and this may have long-term implications for the entire system (Hansom and Rennie, 2003).

Barry Links is owned by the MOD with restricted public access. As a result, the majority of Barry Links, with notable exceptions near the firing ranges on the east coast, is relatively undisturbed and the existing land-use has produced a unique conservational environment. The site has been selected for the GCR on account of the well-preserved parabolic dune system. The pronounced V-shaped parabolic dunes are unique in Britain and demonstrate a close relationship between wind regime and dune orientation (Landsberg, 1956). The site also provides representative examples of beach, dune and links landforms and offers a valuable complement to the study of Tentsmuir on the south of the Tay estuary, which is also of outstanding geomorphological interest (see GCR site report, below).

Conclusions

The extensive sand-covered foreland of Barry Links contains an exceptional series of well-developed and preserved parabolic dunes which are of outstanding geomorphological significance. The dune orientations show a close relationship with local wind regime (Landsberg, 1956) and the pronounced V-shaped form of the Barry parabolic dunes are unique in Britain. The parabolic dunes, which have a mean length-to-width ratio of 3.3:1, have spectacular, elongated, hairpin shapes with an exceptional regular and orderly pattern. These unique characteristics may reflect the open exposure of the foreland, the lack of topographic interference with formative winds and the lack of subsurface control. In addition, Barry Links provides a representative assemblage of many beach, dune and links landforms offering valuable opportunities for studies of coastal evolution.

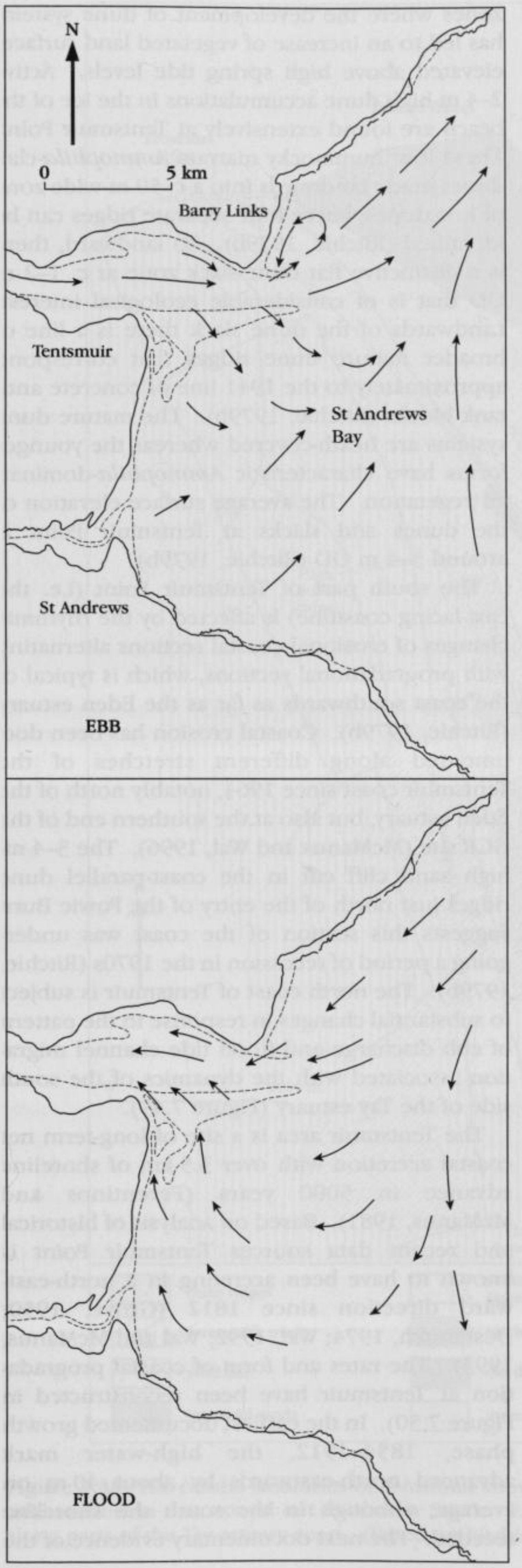

Figure 7.47 Mid-flood and mid-ebb tidal stream patterns in St Andrew's Bay based on a combination of direct measurement and hydraulic modelling. The open coast at Tentsmuir is affected by northward movement on the flood and south-eastward movement on the ebb, whereas the open coast at Barry Links is affected by southward movement on both the flood and the ebb. (After Ferentinos and McManus, 1981.)

TENTSMUIR, FIFE (NO 500 275)

J.D. Hansom

Introduction

The extensive lowland surface of Tentsmuir lies between the Tay estuary in the north and the sandstone headlands of St Andrews in the south (see Figure 7.1 for general location) and is one of the largest areas of blown sand in Scotland (Dargie, 2000). Tentsmuir is a site of long-term accretion with over 3.5 km of shoreline advance in 5000 years (Ferentinos and McManus, 1981). The Tentsmuir GCR site (see Figure 7.42), which includes the vast intertidal sand spits, banks and bars of Abertay Sands, forms the point where the coastline turns from the open sea into the Tay estuary and is of outstanding geomorphological interest. The rate and amount of coastal progradation at Tentsmuir is unique in Britain (Crawford and Wishart, 1966; Ritchie, 1979b) and has been documented by several workers, notably Grove (1950), Deshmukh (1974), Wal (1992) and Whittington (1996). The area is known to have been accreting in a north-eastward direction since 1812 at an average rate of 4.8 m a^{-1} (McManus and Wal, 1996). Long-term net accretion at Tentsmuir is the result of the integrated impacts of several natural processes acting in concert, both wind and wave activity resulting in the accumulation of sediment at the Point (McManus and Wal, 1996). Close relationships between the geomorphological and ecological evolution of Tentsmuir (Crawford and Wishart, 1966; Garcia-Novo, 1976) enhance the scientific interest of this highly dynamic and outstanding site.

Description

The Tentsmuir Point GCR site forms a relatively small proportion of the 3300 ha of sand dune in the greater Tentsmuir area (Dargie, 2000) (Figure 7.48). Low, emerged beach sands and silts form the substrate materials for much of the Tentsmuir links and dune system, however the boundaries between the emerged ('raised') beach sand and blown sand are imprecise (Ritchie, 1979b). Most of the Tentsmuir area was stabilized by afforestation in the 1920s and as a result much of the morphological detail has been obscured. Nevertheless, there is evidence that beneath the forest cover there are sets of sand ridges running parallel to the coast (Ritchie, 1979b), and to the south and west, intervening lochs that have since been drained (Hutcheson, 1914). Structurally, Tentsmuir is composed mainly of two sequences of dune ridges arranged approximately parallel to the nearby coast with intervening slacks. In the north, bordering the Tay estuary, they trend east–west and along the open east-facing coast of St Andrews Bay they trend north–south. At Tentsmuir Point the often rather poorly developed 2–4 m-high dunes are weakly aligned north-west–south-east (McManus and Wal, 1996).

The morphology of Tentsmuir Point is intimately linked to the intertidal sand spits, banks and bars of Abertay Sands that stretch eastwards for 6–7 km beyond the Point (Figure 7.48). Abertay Sands are more than 1 km in width and incorporate a substantial island area at the southern entrance. These sand formations are highly dynamic and respond to the complex interplay of the three main variables, estuarine discharge, tidal streams and wave climate (Ritchie, 1979b). The complex development of the Abertay sand spits and bars, including an analysis of the main ebb and flood channels, is investigated in detail by Green (1973).

Tentsmuir Point provides a complex topography where it is possible to identify fragments of earlier phases of development, including former coastlines that evolved as a result of processes that are essentially similar to those operating today. The low-gradient sand beach at Tentsmuir Point reaches widths of up to 400 m and the lower foreshore typically shows ridge and runnel structures trending north–south (McManus and Wal, 1996). Tentsmuir Point is largely composed of medium-grained sands (D_{50} = 0.28 mm) that are highly susceptible to wind action. Sediment transport by wind is very important in the upper foreshore and backshore zones where the development of dune systems has led to an increase of vegetated land surfaces elevated above high spring tide levels. Active 2–4 m-high dune accumulations in the lee of the beach are found extensively at Tentsmuir Point. These low, hummocky marram *Ammophila*-clad dunes grade landwards into a *c.* 50 m-wide zone of low dunes where four separate ridges can be identified (Ritchie, 1979b). To landward, there is a distinctive flat dune-slack zone at *c.* 1–2 m OD that is of considerable ecological interest. Landwards of the dune slack there is a line of broader mature dune ridges that correspond approximately to the 1941 line of concrete anti-tank blocks (Ritchie, 1979b). The mature dune systems are heath-covered whereas the younger forms have characteristic *Ammophila*-dominated vegetation. The average surface elevation of the dunes and slacks at Tentsmuir Point is around 3–4 m OD (Ritchie, 1979b).

The south part of Tentsmuir Point (i.e. the east-facing coastline) is affected by the rhythmic changes of erosional coastal sections alternating with progradational sections, which is typical of the coast southwards as far as the Eden estuary (Ritchie, 1979b). Coastal erosion has been documented along different stretches of the Tentsmuir coast since 1964, notably north of the Eden estuary, but also at the southern end of the GCR site (McManus and Wal, 1996). The 3–4 m-high sand cliff cut in the coast-parallel dune ridges just north of the entry of the Powie Burn suggests this section of the coast was undergoing a period of recession in the 1970s (Ritchie, 1979b). The north coast of Tentsmuir is subject to substantial changes in response to the pattern of ebb discharge and flood tide channel migration associated with the dynamics of the south side of the Tay estuary (Figure 7.49).

The Tentsmuir area is a site of long-term net coastal accretion with over 3.5 km of shoreline advance in 5000 years (Ferentinos and McManus, 1981). Based on analysis of historical and recent data sources Tentsmuir Point is known to have been accreting in a north-eastward direction since 1812 (Grove, 1950; Deshmukh, 1974; Wal, 1992; Wal and McManus, 1993). The rates and form of coastal progradation at Tentsmuir have been reconstructed in Figure 7.50). In the earliest documented growth phase, 1854–1912, the high-water mark advanced north-eastwards by about 40 m on average, although in the south the shoreline receded. The next documentary evidence of the

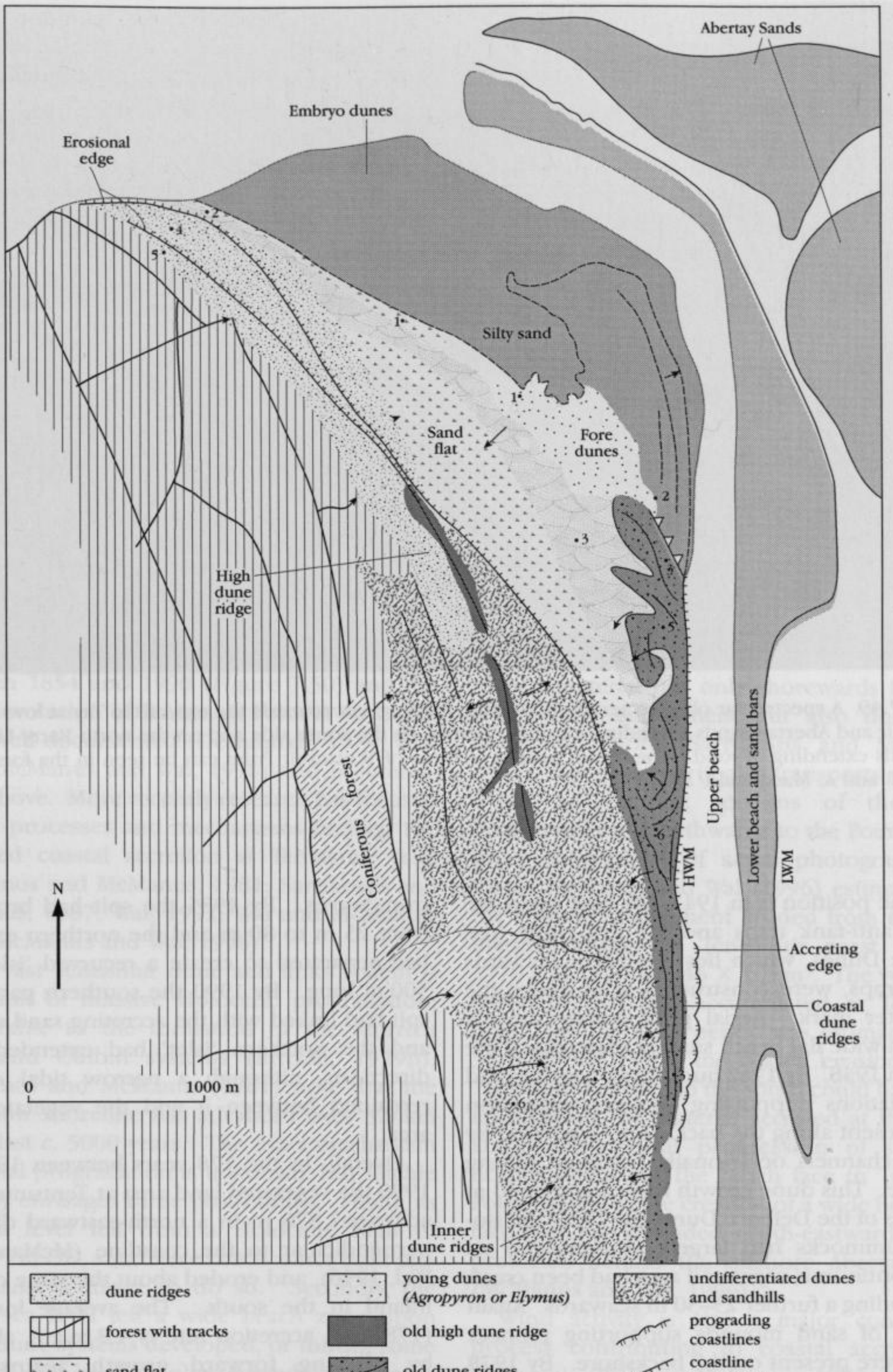

Figure 7.48 The coastal landforms of Tentsmuir showing the extensive areas of sandflat, foredunes and intertidal sandbanks that extend out to Abertay Sands. Erosional edges are found in the south of Tentsmuir and along parts of the Tay estuary coast. (Based on Ritchie, 1979b, and McManus and Wal, 1996.)

Figure 7.49 A spectacular oblique aerial photograph looking east towards the exit of the Tay at low tide with Tentsmuir and Abertay Sands extending into the distance on the south side and on the north Barry Links with Gaa Sands extending beyond. The recent sand accretions of Tentsmuir Point can be seen in the foreground. (Photo: P. and A. Macdonald/ SNH.)

shoreline position is in 1941, the year when the line of anti-tank traps and the low ridge (the Defence Dune), which lies 80–160 m seawards of the traps, were constructed at or above the high-water mark. Aerial photographs show a *c.* 500 m-wide flat beach surface seawards of the dunes in 1948. By 1962 hummocky aeolian sand accumulations supporting pioneer vegetation were present along the backshore, separated by narrow channels occasionally occupied during high tide. This dune growth had extended 40 m seawards of the Defence Dune. By 1972, the isolated hummocks had largely amalgamated so that a continuous vegetated area had been created extending a further 25–30 m seawards. Again a series of sand mounds supporting pioneer plants were present on the backshore. By 1978 the dune margin had advanced a further 60 m seawards as the mounds became incorporated within the vegetated dune area. New actively accreting mounds lay to the seaward. To the east a 400 m-long dune-covered spit extended northwards from Tentsmuir Point, providing shelter from waves. By 1985 the spit had broadened from 25 m to 80 m and the northern extremity had separated to create a recurved 'islet' over 300 m long. By 1990 the southern part of the spit had linked with the accreting sand mounds and the northern 'islet' had extended in all directions, although a narrow tidal channel remained between it and the vegetated land area.

Overall, in the 178 years between 1812 and 1990 the vegetated land area at Tentsmuir Point advanced 870 m in a north-eastward direction perpendicular to the coastline (McManus and Wal, 1996), and eroded about the same distance inland in the south. The average long-term (178-year) accretion rate is 4.8 m a^{-1}, although by plotting forward growth against time McManus and Wal (1996) show that accretion rates have increased greatly through time. The very high rates of accretion have been achieved by the retention of sand upon an already high beach surface. The vegetation has responded to rapid coastal accretion at Tentsmuir, with an out-ward movement of vegetation zones over time (Crawford and Wishart, 1966; Ritchie, 1979b). The pattern of floristic development is matched closely to the distribution of slacks in relation to coastal accretion (Crawford and Wishart, 1966).

Interpretation

Tentsmuir is one of the most rapidly accreting parts of the British coastline (Crawford and Wishart, 1966). Continuing coastal progradation is relatively rare in Britain and most dune systems are currently undergoing a period of retreat. Thus, the natural dynamism of the north-eastwards accretion observed at Tentsmuir Point has attracted considerable scientific interest and research. Grove (1950) first mapped the coastal progradation at Tentsmuir and suggested three main possible sand sources: sediment entering the coastal system from the Rivers Tay and Eden; offshore sediments; or sediment derived from coastal erosion. Later research established the detail of coastal changes between 1854 and 1990 (Figure 7.50) and the recent evolution of Tentsmuir Point is now relatively well documented (Deshmukh, 1974; Wal, 1992; McManus and Wal, 1996) and is summarized above. More recently research has focused on the processes and mechanisms fuelling the observed coastal accretion at Tentsmuir (e.g. Ferentinos and McManus, 1981; Sarrikostis and McManus, 1987; Wal, 1992; Wal and McManus, 1993; McManus and Wal, 1996).

The vast Tentsmuir dune and links system is the result of massive Holocene progradation, comparable to the formation of the Morrich More and Culbin systems (Ritchie, 1979b). Ferentinos and McManus (1981) note that the Tentsmuir shoreline has advanced over 3.5 km in the last *c.* 5000 years. The exact mechanism of coastal progradation is unknown, but Ritchie (1979b) envisages three possibilities. Firstly, as the sea level fell from a Holocene high of *c.* 10–15 m OD, successive beach zones built seawards and continue to do so. Secondly, the falling sea level left a wide beach zone upon which dune systems developed, or thirdly, some form of spit–bar complex curved southwards from the Tay enclosing a broad lagoonal area that was subsequently infilled from the east by blown sand. A detailed stratigraphical and geomorphological investigation is required to elucidate the Holocene evolution of the Tentsmuir system.

Recent process studies at Tentsmuir may provide a key to understanding the past. Tide, wave and wind activity are the major constructive processes contributing to the current growth of Tentsmuir (McManus and Wal, 1996). The floor of St Andrews Bay, an area within which sediments have been deposited during Late-glacial and subsequent times (Browne and Jarvis, 1983), may provide the immediate source of sediment for the Tentsmuir area (McManus and Wal, 1996). Sediments are also swept northwards onto Tentsmuir by a gyre in the flood tide (see Figure 7.47), whereas ebb tides may sweep sediments south, across Abertay Sands (Ferentinos and McManus, 1981). Based on wave refraction analysis, Sarrikostis and McManus (1987) demonstrated that wave fronts approaching the Fife coast from most directions become deformed in such a way that they sweep towards the Tentsmuir area. Consequently, as the result of sediment movement by waves approaching the shore at an angle, Tentsmuir Point experiences accretion due to the transport of bed material not only shorewards from the bed of the embayment but also northwards along the shore (Sarrikostis and McManus, 1987). Longshore drift also transports sediment from the eroding sections of the south Tentsmuir coast northwards to the Point. Based on a comparison of aerial photographs and maps, McManus and Wal (1996) estimated that the volume of sediment eroded from the dune margins along the Tentsmuir coast between 1978 and 1990 was 46×10^4 m^3. The volume of sediment that had accumulated at Tentsmuir Point over the same period was estimated to be 33×10^3 m^3. Thus the coastal erosion on the Tentsmuir beaches to the south could have readily supplied the material accreted at the Point. Long-term natural progression of sediment northwards along the beach face to Tentsmuir Point has led to the creation of a wide beach-surface that has extended north-eastwards and is protected behind the offshore Abertay Sands (McManus and Wal, 1996).

Wind activity is also a major constructive process contributing to coastal accretion at Tentsmuir (Wal and McManus, 1993; McManus and Wal, 1996). By 1990, over 300 m of the 500 m-wide beach surface noted in 1948 was covered with low vegetated dunes. The present area of accretion is now well above the level of spring high-water mark, indicating that the sediment covering the beach surface has been trans-

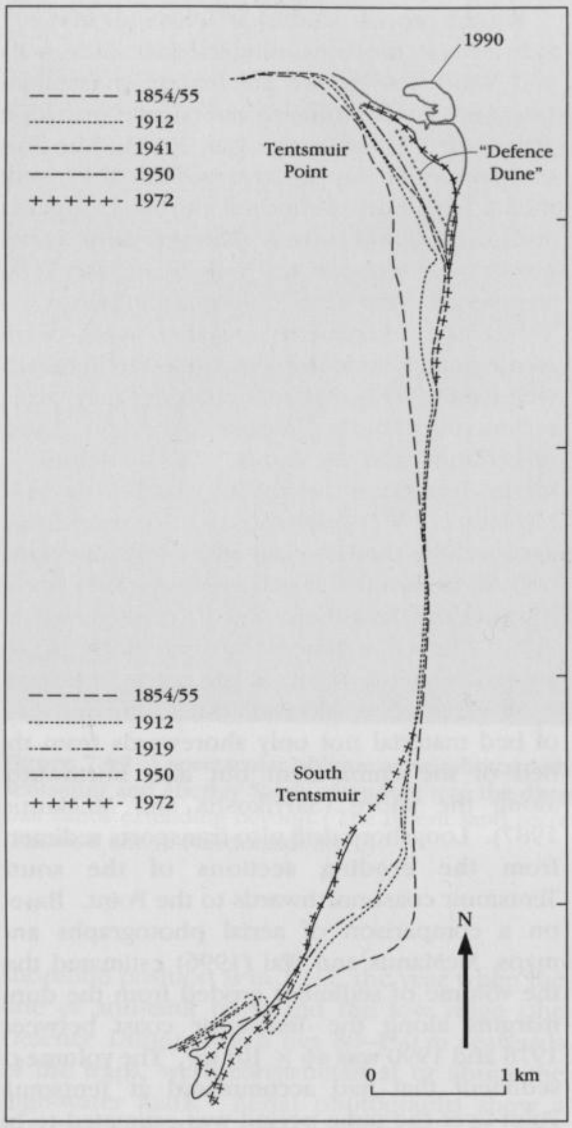

Figure 7.50 Long-term changes in the position of south and north Tentsmuir showing a general trend of erosion in the south and accretion in the north. (Compiled from McManus and Wal, 1996.)

ported to the site by wind action (McManus and Wal, 1996). A detailed study of the wind regime at Tentsmuir identified high-energy seasonal 'unimodal' (offshore or onshore) and 'bimodal' (both offshore and onshore) wind regime patterns (Wal and McManus, 1993). In addition, there can also be a 'unimodal' longshore wind and a 'bimodal' one that possesses a longshore component. Each of the major wind directions initiate sand transport at certain velocities and form a distinctive group of landforms. The commonest offshore winter winds may carry sand from the dunes to create wind-shadow foredunes at the back of the upper beach. Offshore winds also carry sand onto the lower beach and into nearshore tidal waters where wave and tidal activity recycles it to the beach. Therefore, the principal geomorphological impact of offshore winds is the production of shadow foredunes (McManus and Wal, 1996). Onshore winds, common in spring and autumn, transport sand up the beach face, enhancing foredune growth and carrying sand landwards into the dune systems. Longshore winds from the south can transport large volumes along the coast towards Tentsmuir Point (McManus and Wal, 1996). For example, strong winds in November 1968 carried continuous sheets of sand northwards along the Tentsmuir coast for at least three hours forming a swarm of barchan dunes up to 1 m high on the beach at the Point. It is calculated that as a result of this storm, more than 40 000 tonnes of sand were transported to Tentsmuir Point (McManus and Wal, 1996) although much of the sediment was swept north into the channel of the Tay estuary, perhaps to be recycled into the system at a later date.

The close relationship between the geomorphological and ecological evolution of Tentsmuir Point has also attracted considerable research (e.g. Crawford and Wishart, 1966; Desmukh, 1974; Garcia-Novo, 1976; Whittington, 1996). From the wide intertidal beach to the margins of the forest (which is encroaching naturally onto the older dunes) there are excellent examples of the interaction of vegetation and landform, with particular emphasis on accretionary forms and processes. Vegetation zones have encroached seawards gradually stabilizing the accreting coastline. For further details of the biological interests and the complex vegetation successions at Tentsmuir Point see Crawford and Wishart (1966), Steers (1973) or Garcia-Novo (1976).

Conclusions

Tentsmuir Point, Fife, marks the southern limit of the Tay estuary and is one of the most rapidly accreting parts of the British coastline. In contrast to the majority of dune systems in Britain, which are generally undergoing retreat, Tentsmuir Point is actively accreting. Since 1812

Tentsmuir Point has advanced 870 m in a north-easterly direction at an average rate of 4.8 m per year in part, fuelled by erosion of South Tentsmuir. The very high rates of accretion have been achieved by the retention of sand upon an already high beach surface. Net accretion at Tentsmuir Point is the outcome of the integrated impacts of several natural processes acting in concert. Wave activity in St Andrews Bay results in the transport of sediment to the head of the embayment and northerly longshore drift along the Tentsmuir coast encourages progression of sediment along the beach face towards Tentsmuir Point. Wind action acts simultaneously, resulting in the accumulation of low dune forms on top of a wide beach surface. Onshore, offshore and longshore winds are all important in dune formation at Tentsmuir. The outwards movement of dune vegetation zones is related to long-term coastal accretion at Tentsmuir, and this close association between the geomorphological and ecological evolution enhances the scientific interest.

The site is also important as a National Nature Reserve and is part of a Special Area of Conservation.